

Exploiting Short-Range Cooperation for Energy Efficient Vertical Handover Operations*

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Abstract—The availability of multiple collocated wireless networks using heterogeneous technologies and the multi-access support of contemporary mobile devices have allowed wireless connectivity optimization, enabled through vertical handover (VHO) operations. However, this comes at a high energy consumption on the mobile device, due to the inherently expensive nature of some of the involved operations. This work proposes exploiting short-range cooperation among collocated mobile devices to improve the energy efficiency of vertical handover operations. The proactive exchange of handover-related information through low-energy short-range communication technologies, like Bluetooth, can help in eliminating expensive signaling steps when the need for a VHO arises. A model is developed for capturing the mean energy expenditure of such an optimized VHO scheme in terms of relevant factors by means of closed-form expressions. This model is validated through simulations and results demonstrate that the proposed scheme has superior performance in several realistic usage scenarios considering important relevant factors, including network availability, the local density of mobile devices and the range of the cooperation technology.

I. INTRODUCTION

Modern wireless networking is characterized by the availability of multiple radio access technologies, such as Wi-Fi (IEEE 802.11), 3G/4G mobile networks and WiMAX (IEEE 802.16), with overlapping as well as complementary coverage areas. This diversity of available access opportunities, the proliferation of mobile devices equipped with multiple radio interfaces and the impending emergence of next generation (5G) mobile networks present a great opportunity for ubiquitous, always-on connectivity. A necessary ingredient along this way is a mechanism enabling Mobile Nodes (MNs) to seamlessly roam between heterogeneous wireless access networks, commonly referred to as *the vertical handover (VHO)*. Such a mechanism could act as an enabler to a number of critical management operations, like mobility management and offloading.

There exist established standards, including 3GPP [1] and IEEE 802.21 [2], specifying multi-radio mobility management frameworks for the realization of VHOs in a *media independent manner*, i.e., by abstracting the handover actions to isolate them from the details of the underlying radio access technologies. These frameworks include operations relevant to various handover-related aspects, including the issuance of handover triggers, the determination of a list of networks that are candidate handover targets, the selection of a target network among the candidates and the execution of the handover (including related “book-keeping” operations). See, e.g., [3].

While the capability for VHOs undeniably leads to the enhancement of the overall service experience, it comes at a high cost for the mobile devices in terms of energy consumption, since some of the associated operations are inherently expensive. In the present world of battery-limited devices, where always-on availability is becoming increasingly important, there is a clear need for a more energy-aware multi-radio mobility management framework.

With the above in mind, this paper aims at enabling energy-efficient vertical handovers. Towards this end, we make *three novel contributions*. Firstly, we *propose a mechanism to exploit short-range cooperation* among mobile devices as an optimization for improving the energy efficiency of VHO operations (section III). At the heart of the idea is the use of low-energy short-range communication technologies, like Bluetooth, for the periodic exchange of handover-related information between collocated MNs. This information is stored in a cache memory at each MN and is used once a VHO is triggered. The locality of the obtained information helps in reducing or in completely eliminating the number of expensive VHO operations, like scanning, effectively making the whole VHO more efficient.

Secondly, we *develop a performance model* that captures the costs and benefits of short-range cooperation, expressed in terms of average energy expenditure (section IV). The model concisely encapsulates various cooperation and handover-related parameters like the radio link conditions in the area where the handover occurs, network loading conditions at candidate networks, the density of neighbors within the cooperation area, their tendency for associating with each of the candidate networks and the range of the short-range communication technology. All these are important factors when considering handovers and the model manages to wrap them in concise yet descriptive closed-form expressions, also taking into account the cooperation cost.

Thirdly, we *validate the above mentioned model* via simulation, and *perform a study exploring the effect of the relevant parameters* to the performance of the cooperation-assisted handover scheme by employing both simulations and the model and also involving a comparison with the conventional approach (section V). The results present several realistic scenarios in which the cooperation-assisted scheme is seen to outperform the conventional VHO approach. Through these results, we find that the most important factors influencing the efficiency of the cooperation-enabled mechanism are: the average network load, the density of neighbors within the cooperation area and their association preference with specific networks.

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In terms of related work, there have been several works employing short-range cooperation as a means for optimization from various perspectives (e.g., [4], [5], [6], [7], [8], [9]) but to the best of the authors' knowledge this is the first attempt to exploit this concept in the domain of VHO management. In the context of VHO management, the closest in spirit to our work is the one reported in [10] where geolocation information is exploited for improving quality of experience but it does not involve short-range cooperating peers nor does it target energy-efficiency. Regarding the modeling aspect of this paper, this is the first attempt at a comprehensive modeling of the energy costs associated with vertical handover mechanisms. The only other work bearing some relevance is [11], which investigates the energy requirements associated with the execution of VHOs. However, [11] addresses only conventional handover frameworks and proceeds on the basis of direct measurements on a prototype heterogeneous network testbed.

In the following section, we give a brief overview of the media independent handover (MIH) operations and their associated energy efficiency bottlenecks, providing the conceptual basis for developing the paper's novel contributions described in subsequent sections.

II. MEDIA INDEPENDENT HANDOVER OPERATIONS AND ASSOCIATED BOTTLENECKS

To motivate our proposed short-range cooperation mechanism as an enabler of fast and energy-efficient handovers, we give a brief overview of conventional media independent handover schemes according to the prevalent standards, such as 3GPP [1] or IEEE 802.21 [2]. While each vertical handover framework defines its own entities and a different set of actions and messages, the essence of the handover-related operations remains the same in all frameworks. Thus, the following review of important operations (from this paper's perspective) is expressed in generic terms, and is confined to operations essentially relevant to this study.

Once a vertical handover is triggered, the MN queries an information service for a list of candidate networks, i.e., networks serving the area where the MN is located and accessible by means of a radio access technology among those supported by the MN. While all such networks in the list are in principle candidates for becoming the target of the handover, there is no guarantee that all of them will actually be available to the MN. One reason might be that the radio link to a candidate network might be poor due to a bad positioning of the MN, despite the fact that the network covers the local area. Therefore, the MN needs to scan candidate networks to verify the link quality by measuring the received signal strength (RSS).

Furthermore, even in the case that a candidate network is accessible to the MN through a radio link of good quality, it must also have adequate resources to allocate in order for an association to be performed. Thus, apart from scanning, the MN needs to query the available networks for resources. If both of these operations are successful, the network can be chosen as a target for handover. Among the actions just outlined there have been studies, e.g. [11], showing that the scanning operation can be very costly in terms of energy, even by an order of magnitude or more. Moreover, consulting the information service is an action that can incur latency to the

whole vertical handover process, since such a service could be located in a server multiple hops away.

The generic operations just described can be combined in several ways to form a complete handover scheme. For example, the MN could scan all the candidate networks at once and then query those in which the scan was successful for resources. Fig. 1 illustrates one such commonly employed scheme, referred to here as SCAN-FIRST. The scheme begins with the MN getting a list of the candidate networks by the information service. Each network is examined in turn, by a scanning to check whether the radio link quality is good, followed immediately by a query for resources in case of a successful scan. The first network for which both operations succeed is chosen as the handover target, without checking the rest of the networks contained in the candidate networks list.

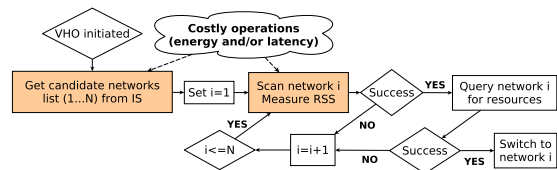


Fig. 1: VHO procedure in the SCAN-FIRST scheme

In the remainder of this paper we will adopt SCAN-FIRST as a reference “conventional” scheme and as a basis for deploying the short-range cooperation-assisted enhancement to be proposed. However, it is equally possible to employ the proposed short-range cooperation assistance in conjunction with any alternative arrangement of the conventional handover base-operations. Correspondingly, the associated performance model of Section IV can be readily adapted for such alternatives.

III. EMPLOYING SHORT-RANGE COOPERATION FOR EFFICIENT VHOs

The idea behind the short-range cooperation mechanism is that an MN does not wait for a handover trigger to occur to start collecting network-related information. Instead, it continually exchanges relevant information with peer MNs, employing a short range wireless technology. This arrangement opens the possibility that some costly handover-related actions that would be mandatory in conventional media independent VHO schemes, like scanning and consulting the information service, could be avoided when the need for a handover arises.

More specifically, each MN periodically broadcasts information about the network it is currently connected to (frequency, name etc.) using a low-energy short-range communication interface (e.g., Bluetooth). Each listening MN gathers the information broadcast by its neighbors and updates a cache of candidate networks, so that it can be used later, once a VHO is initiated. The more short-term the cache is, the more relevant and accurate the information will be for the MN.

A. Selecting an Appropriate Short-Range Cooperation Protocol

Since the cooperation mechanism is employed for improving the energy efficiency of VHO operations, allowing the MNs to keep their short-range interfaces continuously active, constantly listening for broadcast information from collocated peers would

not be advisable, as it would lead to high energy consumption even in cases of energy-efficient technologies like Bluetooth low energy (BLE). It would thus be preferable if the MNs periodically deactivated their short-range interfaces to save energy and activated them only in the case they needed to exchange context information. However, the energy savings of this approach come at the cost of a more difficult coordination among the cooperating nodes, because such coordination can occur only during the periods the MNs are active. Therefore, an asynchronous power-saving mechanism is required, to allow the coordination among MNs in a simple manner and without the need of exchanging additional control messages.

There are several works on efficient cooperation mechanisms. However most of them are cumbersome for our purpose. For example, [12] requires devices with GPS positioning, [13] needs a secondary radio interface for paging, while some works, e.g., [14] and [15], propose sophisticated broadcast mechanisms with high energy requirements.

The solution adopted in this work is based on [16], which proposes power-saving MAC protocols for information exchanges in IEEE 802.11-based ad hoc networks. Ref. [16] proposes three protocols, namely the dominating-awake-interval, periodically-fully-awake-interval and quorum-based protocols, which allow mobile hosts to switch to a low-power sleep mode periodically. After assessing these protocols in terms of their energy efficiency, we chose for this work a slight modification of the periodically-fully-awake-interval protocol as it best matches our application setting — it was shown to provide much better performance energy-wise compared to the other two [16].

The modification employed here over the original in [16], is that the protocol is targeted to operate above the MAC layer. The reason is that the same solution can be applied over different communication technologies without changing its basic concept. Another reason is to accommodate the possibility that the short-range communication interface could also be used simultaneously by other processes for different operations. Optimizing the wireless technology at the MAC layer to work solely for the cooperation mechanism might have unpredictable and unwanted side-effects for the rest of the processes. By applying the coordination protocols at a higher level, the cooperation mechanism can be used to save energy as intended, while allowing the operations of other processes to be performed unchanged (e.g., by using the short-range interface during the idle-periods of the cooperation mechanism).

We now briefly review the main features of periodically-fully-awake-interval in generic terms, avoiding MAC details unrelated to our setting. According to the protocol, each node operates using its own clock, without making any assumptions for the clocks of other MNs. Information exchanges occur in beacons, each lasting for a time equal to *Beacon Interval* (BI), further subdivided in periods where the MN can transmit (*Advertisement Window* - AW) and receive (*Listening Window* - LW) context information from nearby MNs or remain idle. Normally, beacons just transmit and stay idle for the rest of their duration. However, every j^{th} beacon is fully active and transmitting is followed by a listening phase. The parameters BI, AW, LW and j are global, applying to all MNs. This mechanism is illustrated in Fig. 2 for two nodes and for $j = 3$.

The scheme guarantees that a node will be heard by its

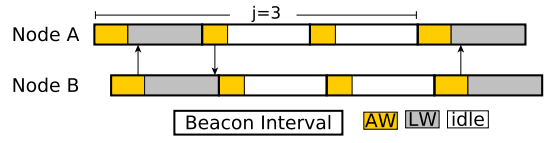


Fig. 2: Modified *periodically-fully-awake-interval* protocol for the short-range cooperation between MNs. Neighbors exchange VHO related information during AW and LW periods.

neighbors within j beacons regardless of how much their clocks drift away [16]. It is easy to see that, by using more low energy beacons than fully active ones, large idle periods can be obtained, during which little or no energy will be consumed by the short-range interface. The greater the value of j , the higher the energy savings from the idle periods become, at the expense of slower updates of handover-related information.

B. Exploiting the Information Exchanged through Short-Range Cooperation for Vertical Handovers

Once a VHO is triggered, the MN attempts to connect to a suitable candidate network among those suggested by its neighboring nodes, simply by consulting the information stored in its cache. Cache entries are tagged with a timestamp showing the time they were introduced in the memory and remain stored based on a threshold value showing how recent they are. The lower the threshold, the faster an entry needs to be evicted from the cache. As long as the information held in the MN's cache is recent and comes from collocated MNs (due to the short-range technology employed for cooperation), the MN does not need to verify the radio links for networks in the cache and just queries each of the candidate networks in the cache for resources, without scanning first. If none of the networks in the cache has adequate resources to support connectivity, the MN falls back to the conventional VHO scheme and the list of candidate networks is checked by the procedure described in Section II, after a preprocessing to remove networks for which a connection attempt has already been made. The steps performed by the MN when the short-range cooperation mechanism is enabled are illustrated in Fig. 3.

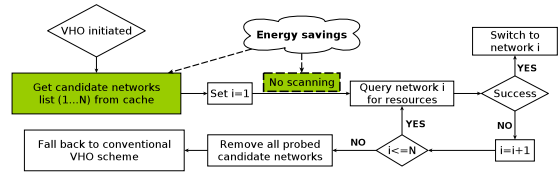


Fig. 3: VHO procedure using the information obtained through the short-range cooperation mechanism

The way that the short-range cooperation mechanism operates can have multiple advantages over a conventional VHO scheme. The most important advantage is that the information exchanged using this approach can help in eliminating inherently expensive signaling steps, in terms of energy or latency, when the need for a VHO arises. More specifically, as already explained, since a short-range technology like Bluetooth is used, the information obtained will be accurate for the MN with a very

Parameter	Description
p	Probability of sufficient radio link quality
q	Probability of availability of network resources
N	Number of candidate networks
$v_i, i = 0 \dots N$	Network preferences of cooperating peer
σ	MNs per unit area
r	Communication range of short-range technology
C_{IS}, C_{SCAN}, C_Q	Cost for consulting the information service, performing a scan and querying a network for resources
T	Average time between two consecutive VHOs
BI	Beacon interval
j	Interval between two fully active beacons
E_{AW}, E_{LW}, E_{IDLE}	Total energy consumed during an AW, LW or idle period

TABLE I: Summary of model parameters

high probability, allowing the omission of expensive scanning operations for ensuring network connectivity. Additionally, the MN can attempt to perform the VHO using its cache entries, without consulting the information service, effectively reducing the handover latency. It should be noted that this improvement does not come with the price of a latency penalty for using the cooperation mechanism, since the coordination of MNs is a proactive process running constantly in the background.

IV. MODEL FOR QUANTIFYING THE BENEFIT OF THE COOPERATION-ASSISTED VHO MECHANISM

We now develop a model to quantify the cost associated with the cooperation-assisted VHO mechanism, in terms of the availability and status of the candidate networks, the node density in the cooperation area and the radio link between these MNs and the candidate networks. Cost is quantified as the mean energy consumption experienced by an MN per handover. For the cooperation-assisted mechanism, the cost can be divided into two parts: the cost for the coordination and information exchanges of the MNs; and the cost for performing the actual VHO procedure. For the conventional scheme, the only cost involved is that for performing the actual VHO procedure.

A. Mean Cost for Performing Vertical Handovers

1) *Conventional Scheme*: We first refer to the average cost per handover in the conventional scheme. We consider an observed MN for which the handover process is initiated. This MN needs to discover candidate networks and attempt to select a handover target among them. However, locally available candidate networks are not guaranteed to be accessible to the MN. We use a parameter p (Table I) to designate the probability that the observed MN will have a radio link of sufficient quality to a candidate network. The parameter p characterizes location idiosyncrasies with respect to radio conditions, so it is assumed that the same parameter value applies to all candidate networks in the area. A p close to 1 indicates that the area around the observed MN (and its short-range neighbors) is associated with good radio conditions, while low values of p indicate poor radio conditions.

Even with good radio conditions, there is no guarantee that the observed MN will manage to associate with a given candidate network, since the network might not have adequate resources to allocate, due to network overload. To capture such loading considerations, we introduce a different parameter q as the probability that a candidate network queried for resources

towards becoming a handover target will respond positively. In the interest of capturing the overall impact of overloads versus normal loading conditions and of keeping the parameter space simple, a common value of q is applied uniformly (but independently) to all candidate networks of the observed MN. Note that (in contrast to the relation of p to the radio link conditions) values of q close to 1 indicate low or moderate network load, while values closer to 0 indicate overload.

Given the link and load parameters just discussed, we now turn to the VHO operations performed in the conventional scheme (Fig. 1). First, the observed MN needs to contact an information service in order to obtain a list of candidate networks. Then, the MN needs to scan each of these networks in turn, to verify the link quality. If, along this process, a candidate network is successfully scanned, the MN will query this network for resources and will make it the handover target if the reply is positive, terminating the handover process. Each of these VHO related operations incurs some cost for the MN. Let C_{IS} , C_{SCAN} and C_Q be the cost for consulting the information service, for performing a scan and for querying a network for resources, respectively.

Denote by N the number of candidate networks available for the observed MN. In contrast to the other parameters discussed above, N is an attribute of the observed MN alone. Different MNs subject to handover will in general be associated with a different number of candidate networks each. The total mean cost per handover will be equal to

$$C_{conv}(N) \triangleq C_{IS} + (C_{SCAN} + pC_Q) \frac{1 - (1 - pq)^N}{pq}. \quad (1)$$

The terms in (1) encapsulate the cost of querying the information service and the mean cost for scanning and querying the N candidate networks for resources, taking into consideration both successful and failed attempts through parameters p and q . The proof of (1) is omitted due to lack of space.

2) *Short-Range Cooperation-Assisted Scheme*: We now turn to the per handover cost for the short-range cooperation-assisted scheme. Again, N candidate networks are assumed available for the observed MN subject to handover. However, while the N networks are a priori available, the MN might not be aware of their existence. A given network among the candidates will be known to the MN only if at least one of its short-range neighbors is connected to it and has provided the relevant information to the MN in question. Therefore, in order to assess the probability with which a candidate network is known to the MN we need to model the existence of short-range neighbors.

For this, we draw upon the notion of a homogeneous Spatial Poisson Process, as follows. The devices that can act as short-range peers are assumed to occur according to a spatial Poisson process of density σ (expressed in devices per unit area) and the radio technology employed for the short-range cooperation is assumed to feature a communication range r , covering an area equal to πr^2 . Then, the number of devices within range from the observed MN follows a Poisson process of rate $\rho = \sigma \pi r^2$. Clearly, this rate encapsulates combined information about device density and about the range of the short-range communication technology.

We now express the preferences of the short-range cooperating peers for the candidate networks available to the

observed MN. Specifically, let $v_i, i = 0 \dots N, \sum_{i=0}^N v_i = 1$, be the probabilities that a random cooperating peer would prefer connecting to candidate network i . The parameter v_0 , in particular, expresses the probability that peer MNs would prefer a network not among the candidate networks of the observed MN, for example a subscription-based network or a network for which the observed MN does not have the proper wireless interface. Note that, like N , the probabilities $v_i, i = 0 \dots N$, are an attribute specific to the observed MN. Other MNs may be associated with a different set of v_i values and a different value for N .

An a priori preference of a cooperating peer for a particular candidate network is not sufficient for associating with it. As was the case of the conventional VHO, the association presupposes the existence of an adequate radio link and the availability of network resources. In view of the relevant parameters p and q , it follows that the probability with which a random cooperating peer will be associated with candidate network i is equal to

$$P_i = qp v_i, \quad i = 1 \dots N. \quad (2)$$

Consequently, the peer will be connected to a network not among the candidates (or not connected at all) with probability

$$P_0 = 1 - \sum_{i=1}^N P_i = 1 - pq(1 - v_0). \quad (3)$$

Given the probabilities in (2) and (3) as well as the splitting property of the Poisson process, the counting processes relevant to the short-range neighbors of the observed MN connected to network i occur as independent Poisson processes of rates ρP_i .

As already discussed in Section III, each MN has a cache in which the networks discovered through the short-range cooperation mechanism are stored. The observed node will have some network i stored in its cache only if at least one of its discovered neighbors was connected to this network. In view of the Poisson structure just discussed, this event occurs with probability

$$w_i = 1 - e^{-\rho P_i} \quad (4)$$

and the associated indicator function of the event is 1_i . The total number of networks for which information is available through the short-range cooperation mechanism will be $\aleph = \sum_{i=1}^N 1_i$ with distribution

$$\pi_m \triangleq Pr\{\aleph = m\}, \quad m = 0, \dots, N. \quad (5)$$

Conditioned on the event $\aleph = m$, the MN will check the m networks and successively try to connect to them. The associated conditional mean cost is denoted by $L_c(m)$. If the process just mentioned fails, the MN will fall back to the conventional VHO approach, by consulting the information service and performing scans in order to discover the available candidate networks. In this case, from the N candidate networks provided by the information service, the MN will only check the remaining $N - m$ networks that were not discovered by the short-range cooperation mechanism.

The conditional mean cost of checking the m networks is

$$L_c(m) = C_Q \left[\sum_{l=1}^m l(1-q)^{l-1} q + m(1-q)^m \right] = C_Q \frac{1 - (1-q)^{m+1}}{q}. \quad (6)$$

As this expression reflects, the mean cost includes the cost of successfully connecting to one of the m networks or of failing to connect to any of them. Additionally, it can be observed that the only operation cost this expression includes is related to performing resource queries to the candidate networks. This is in accordance with the description of the cooperation-assisted VHO mechanism, in which scanning and consulting the information service are omitted until all networks discovered through the short-range mechanism have been investigated.

Using (5) and (6), the unconditional mean cost L_c for inspecting and possibly connecting to some candidate using the short-range cooperation mechanism can be obtained as

$$L_c = \sum_{m=0}^N \pi_m L_c(m) = C_Q \frac{1 - \phi(1-q)}{q}, \quad (7)$$

where $\phi(z)$ is the generating function

$$\phi(z) = Ez^{\aleph} = \prod_{i=1}^N Ez^{1_i} = \prod_{i=1}^N (1 - w_i + w_i z). \quad (8)$$

Moreover, by recalling that the check of the m candidates fails with probability $(1-q)^m$ and by employing (1), one can readily calculate the mean cost associated with the ‘‘backup’’ conventional VHO scheme, employed after failing to connect to m networks recently used by neighboring nodes. Specifically,

$$L_r = \sum_{m=0}^N \pi_m (1-q)^m C_{\text{conv}}(N-m) = C_{\text{IS}} \phi(1-q) + (C_{\text{SCAN}} + pC_Q) \frac{\phi(1-q) - (1-pq)^N \phi(\frac{1-q}{1-pq})}{pq}. \quad (9)$$

The average total cost for performing the handover is $C_{\text{coop}} = L_c + L_r$, so by combining (7) and (9), we get:

$$C_{\text{coop}} = C_{\text{IS}} \phi(1-q) + C_Q \frac{1 - (1-pq)^N \phi(\frac{1-q}{1-pq})}{q} + C_{\text{SCAN}} \frac{\phi(1-q) - (1-pq)^N \phi(\frac{1-q}{1-pq})}{pq}. \quad (10)$$

Typically, C_{SCAN} dominates the other cost constants by an order of magnitude. This observation, together with the fact that when the number of candidate networks N is not too small $(1-pq)^N \ll 1$, leads to a simplification of the exact form (10), expressed by the approximation

$$C_{\text{coop}} \approx C_{\text{SCAN}} \phi(1-q)/pq \approx C_{\text{conv}} \phi(1-q) \quad (11)$$

using also (the approximate form of) (1). Expression (11) links the mean cost of the cooperation-assisted VHO mechanism (excluding the cost for the information exchanges), to the mean cost for the conventional VHO approach. The improvement factor is seen equal to $\phi(1-q) < 1$.

B. Energy Consumption for Mobile Node Coordination

Let T be the average time between two consecutive VHOs. Also, let $E_{\text{AW}}, E_{\text{LW}}$, and E_{IDLE} be the total energy consumed by the mobile node during an AW, LW or idle period, respectively. E_{IDLE} could be set either to a low value, if the interface used

for short-range cooperation has entered a power saving mode, or to zero if it is completely deactivated.

As already discussed in Section III-A, the coordination scheme employs one fully active beacon every j beacons. This means that one round of this scheme is completed after time equal to $j\text{BI}$ and thus the total number of rounds performed in the interval between two consecutive VHOs will be $\frac{T}{j\text{BI}}$ on average. Moreover, it is easy to see from Figure 2 that the energy required for one round will be $jE_{\text{AW}} + E_{\text{LW}} + (j-1)E_{\text{idle}}$. Therefore, the total energy, E_{coord} , spent on average by the coordination mechanism between two VHOs will be

$$E_{\text{coord}} = [jE_{\text{AW}} + E_{\text{LW}} + (j-1)E_{\text{IDLE}}] \frac{T}{j\text{BI}}. \quad (12)$$

V. VALIDATION AND PERFORMANCE EVALUATION

A. Model Validation via Simulation

To validate the model from the previous section we employed a customized version of the well-known ns-3 simulator, enhanced with cooperation-assisted VHO capabilities. The cooperation mechanism was implemented in the form of an application running on top of the MAC layer of the MNs and operating according to the protocol described in Section III. Short-range communications between neighboring devices were confined within a range of $r = 15\text{m}$. The duration of a beacon and the interval between two fully active beacons were set equal to $\text{BI} = 3.2\text{s}$ and $j = 12$, respectively. The costs of individual VHO-related operations were set based on the measurements in [11] ($C_{\text{Q}} = 0.02\text{ J}$, $C_{\text{SCAN}} = 8.6\text{ J}$ and $C_{\text{IS}} = 0.02\text{ J}$), while the power consumption for transmission and reception through the short-range technology was set based on the Bluetooth measurements in [17] ($E_{\text{AW}} = 0.08\text{ J}$ and $E_{\text{LW}} = 0.07\text{ J}$ respectively). It was also assumed that during the idle period the short-range interface is disabled, thus $E_{\text{IDLE}} = 0$.

The simulation scenarios under study involved 10 different wireless networks in an area where short-range communications and handover operations were captured in a square grid of 0.09 km^2 . These networks were divided into 2 types; $N_A = 3$ networks were of type A, representing networks offering premium services and the remaining $N_B = 7$ were of type B, representing open-access networks. In a similar manner, $\alpha_I = 10\%$ of the participating MNs were assigned to the device class I and the remaining $1 - \alpha_I$ to the device class II. The MNs of class I were capable of associating with all $N_A + N_B$ networks, while the MNs of class II could associate only with the N_B open-access networks. It should be mentioned that devices of class I were assumed to have no preference in associating with candidate networks of type A or B, i.e., networks were not ordered based on their classes.

Various device densities were considered for multiple use cases, from rural environments with only a few devices operating in a wide area, to dense urban areas. The number of MNs participating in a simulation run was calculated by multiplying the device density parameter value of the scenario under study to the area of the simulation grid. The evaluated densities were based on the density measurements in [18]. With respect to mobility and since the short-range cooperation mechanism is mostly affected by the average nodal density without regard for the exact mobility pattern, we employed the standard random waypoint mobility model already available in

the ns-3 simulation platform. The MNs could freely move in and out of the area under study with random speeds of up to 10 m/s . It is noted that the mean time between VHOs was not set to a static, arbitrary value. Instead, it was determined through preliminary simulation runs for each scenario considered, by measuring the number of VHOs (triggered by an RSS threshold criterion) experienced by mobile nodes in a predefined amount of time.

In order to properly match the parameters of the analytical model to the simulation setup, the network preferences v_i of the short-range cooperating peers were set, depending on the class of MNs they refer to, according to the number and type of networks, previously mentioned. Specifically, MNs of class I have access to all $N_A + N_B$ networks, so they are associated with a set of probabilities v_i^I , $i = 0, \dots, N_A, N_A + 1, \dots, N_A + N_B$. Of these, the indices $i = 1, \dots, N_A$ refer to the probability with which a random short-range peer (which may belong to any of the MN classes I or II) may associate with the indexed network of type A. The remaining indices $i = N_A + 1, \dots, N_A + N_B$ refer at random peers' association with networks of type B. Correspondingly, MNs of class II are associated with a set of probabilities v_i^{II} , $i = 0, \dots, N_B$, where indices $i = 1, \dots, N_B$ refer at random peers' association with networks of type B.

For the devices of class I, the N_A networks of type A can only be discovered through neighbors that also belong to class I. Each of these neighbors would prefer to associate with any of the N_A networks with equal probabilities $1/(N_A + N_B)$ and since these MNs form α_I of the total population, the probabilities v_i^I , $i = 1 \dots N_A$ become $\alpha_I/(N_A + N_B) = 0.01$. For the remaining N_B networks of type B, each MN assigned to class I would have a preference of $1/(N_A + N_B)$, while each MN assigned to class II would have a preference of $1/N_B$. As a result the probability v_i^I , $i = N_A + 1 \dots N_A + N_B$ becomes $\alpha_I/(N_A + N_B) + (1 - \alpha_I)/N_B \approx 0.139$. Based on this, it follows that $v_0^I = 1 - \sum_{i=1}^{N_A+N_B} v_i^I = 0$. Using similar arguments to that of the previous case, the probability v_j^{II} , $j = 1 \dots N_B$ becomes equal to $\alpha_I/(N_A + N_B) + (1 - \alpha_I)/N_B \approx 0.139$ and therefore $v_0^{II} = 1 - \sum_{j=1}^{N_B} v_j^{II} = 0.03$.

The final parameters required for the comparison of the model results to the simulations are the link quality p and the network load q . These parameters are inherent to the scenario under study and therefore again matched to the simulation setting. The value of parameter p was obtained through the following methodology: a simulation run was performed for 300s with 100 MNs using the conventional VHO scheme. During this period the total number of handover requests was recorded for each MN along with the number of handover request timeouts due to no reply from the network. The parameter p was then calculated by averaging the ratio of timeouts to the total number of handover attempts for all the MNs. The idea behind this approach is that the reason of the timeout was that handover-related messages were lost by the MN or the network due to bad signal quality while the MN was moving. Parameter p was found to be equal to approximately 0.4, corresponding to an average link quality.

The value of parameter q was calculated in a similar manner with the difference that instead of recording the number of handover request timeouts, we recorded the rejection messages

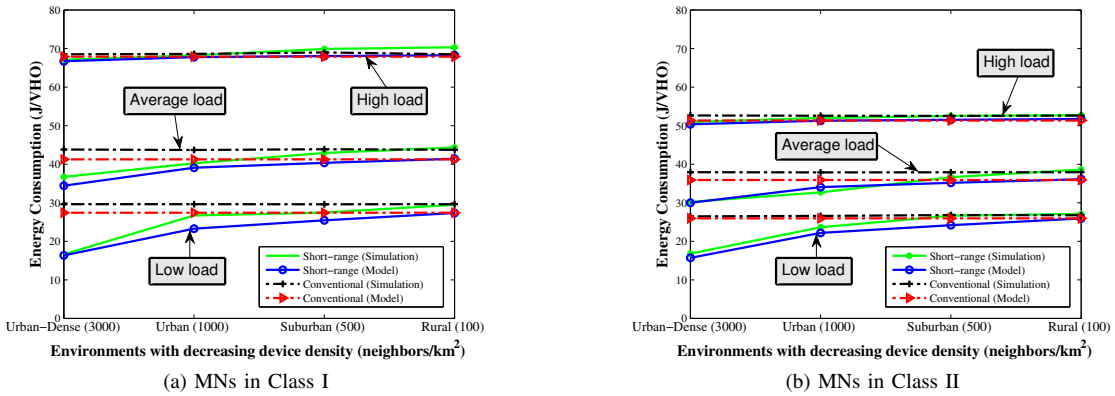


Fig. 4: Simulation and model-based average energy consumption of the cooperation-assisted VHO mechanism compared to that of the conventional VHO scheme for various network loads and device densities.

sent by the candidate networks to association requests due to no resources being available. While the parameter p depends on the simulation topology, q depends on the network resources that can be allocated to the associated MNs. Therefore, in order to simulate different mean network loads we varied the number of MNs that each access point could accept, with higher thresholds leading to lower mean network loads and vice versa. Using this methodology, we managed to achieve low, average and high network loads corresponding approximately to a value of 0.85, 0.5 and 0.15 for the model parameter q .

Based on this methodology, we performed simulations with various device densities and network loads for both classes of MNs. The results can be seen in Fig. 4 in comparison to the results of the analytical model when using the parameters derived from the simulation setting. It is noted that results for the cooperation-assisted VHO include both the energy spent for the short-range cooperation protocol and the energy for selecting a handover target. As it can be observed, the simulations validate the model with both approaches giving very similar results for all the cases under study. Moreover, it can be seen that the cooperation-assisted scheme can be more energy efficient compared to the conventional scheme in several interesting cases, becoming worse only in rural areas where the discovery of neighboring nodes would be a rare event. It is worth mentioning that the conventional scheme yields the same results regardless of the scenario, since the only thing that changes is the nodal density, which for the conventional case is an irrelevant factor.

On a second look, we can also observe that the mean energy consumed per handover and the average network load follow similar trends, with high network loads leading to a much higher energy consumption for both classes of devices. Moreover, it can be seen that higher network loads can negate the benefits of the cooperation-enabled mechanism even in very dense environments. This is because handover attempts will fail with a very high probability, regardless of the number of networks discovered through cooperation and therefore a larger number of networks will need to be queried for resources, increasing the mean energy consumption. Moreover, we can observe that devices of class II have a lower mean energy consumption compared to devices of class I in all cases, with the gap increasing as the network load increases. This is intuitive, since devices of class I have a wider range of networks to choose from and therefore they will spend more energy on

average, while querying a larger number of candidate networks. As a final remark, we can see that using a global “average” value of q works well, even in setups with multiple network classes, as the one simulated.

B. Further Numerical Results based on the Model

Having validated the model developed in section IV, we can now use it to expand our evaluation of the cooperation-enabled VHO mechanism. For the results in this subsection, we assume that all MNs belong to the same class and that all candidate networks are of the same type. Moreover, the average time T between consecutive handovers is set to 300s and the device density is fixed to $\sigma = 0.003$ neighbors/m² corresponding to a dense urban area. The link quality and network load parameters p and q are adjusted according to the evaluation scenario under study, while the remaining parameters of Table I are kept the same as the ones described in Section V-A.

We begin by evaluating the energy consumption of the cooperation-assisted VHO mechanism and comparing it to that of the conventional scheme described in Section II. The evaluation is made in terms of the number N of available candidate networks in the area of the MN and of the various network preferences of its neighbors, expressed through the values of v_i . More specifically we examine the performance of the cooperation-assisted VHO scheme in an area with networks of low average load ($q = 0.9$) and good link quality ($p = 0.8$) for three scenarios. The first scenario (I in Fig. 5a) corresponds to a setting where the short-range neighbors of the observed MN exhibit comparable preference to the candidate networks available to the observed MN. This is modeled by $v_i = 1/N, i = 1 \dots N$, and $v_0 = 0$. This could be a typical scenario in which all the wireless networks available in an area use only well-known technologies that are not subscription-based. For the second scenario (II in Fig. 5a), two candidate networks are assumed to be unpopular to the short-range neighbors. This is modeled by employing $v_0 = 0, v_s = 0.1$ and $v_h = (1 - 2v_s)/(N - 2)$, where v_s is the probability of unlikely networks and v_h the probability of networks that are likely to be preferred. In this case it only makes sense to consider scenarios of at least $N = 3$ networks (the 2 unpopular and at least one popular). Finally in case III we give a small probability to all the networks and let v_0 to be close to 1. This could be a scenario in which the MN has unusual wireless interfaces, e.g. a WiMAX interface in an area where WiMAX is uncommon.

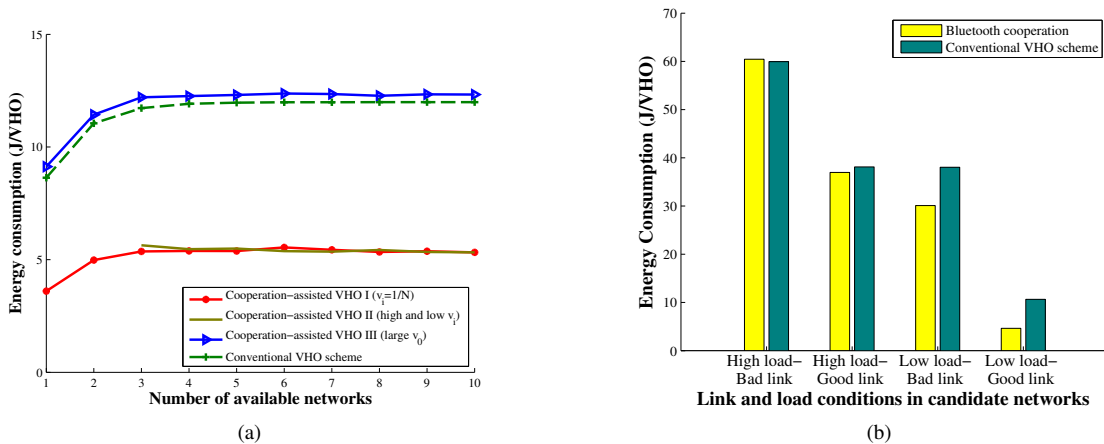


Fig. 5: Average energy consumption of the cooperation-assisted VHO mechanism compared to that of the conventional VHO scheme in terms of the number of available networks and the network preference of the cooperating neighbors (5a) and for various radio link and network load conditions (5b).

Energy results for the three scenarios and for the conventional VHO scheme are displayed in Fig. 5a as a function of candidate networks N . As it can be observed, the average energy consumed in case I is up to 50% lower than that of the conventional scheme. An MN performing a handover in an environment with the characteristics of case I will most likely discover candidate networks through its short-range neighbors, avoiding the costly scans of the conventional scheme. Moreover, we can see that as the number of candidate networks increases, the average energy consumption per handover gradually converges to a limiting value. This is because as the number of network increases, the observed MN will probably manage to connect to one of the first few networks discovered using the short-range cooperation approach and thus, no matter how many networks were actually discovered, no attempt of querying for resources or connecting will be made to most of them.

For case II, the short-range cooperation assisted scheme performs marginally worse than in case I when the number of candidate networks is small, but gets even as the number of networks increases. Since we keep the number of networks that have a low v_i fixed, then for a small total number of networks the probability of discovering one of them through short-range cooperation will be low, forcing the MN most of the times to fall back to the conventional VHO scheme (and to a higher energy consumption). However, as the number of networks increases, the highly-probable networks become the majority, meaning that the likelihood of the MN discovering networks through short-range cooperation increases, reducing the probability that a costly scan will be required. Therefore, the existence of some unpopular networks becomes immaterial and the performance converges to that of scenario I.

Finally, for scenario III the short-range cooperation assisted scheme exhibits lower performance, worse even than that of the conventional. In the case that v_0 is close to 1 the cooperation-assisted scheme spends almost the same amount of energy as the conventional one for performing the actual handover procedure. However, the cooperation scheme has the additional overhead of executing the short-range cooperation protocol and this leads to a higher total energy consumption.

Turning to a different aspect, we now examine the performance of the VHO scheme as a function of the parameters

related to the radio link conditions in the area (expressed through p) and the load of candidate networks (expressed through q) to the average energy consumption of both the conventional and the cooperation-assisted VHO schemes. We consider various combinations of the radio link conditions (good corresponds to 0.9 and bad to 0.2) and loading conditions at the candidate networks (high corresponds to 0.2 and low to 0.9). The results are shown in Fig. 5b.

We can observe that in the first two cases where the load is high, the conventional scheme is almost on par with the cooperation-assisted one regardless of the link quality. On the other hand, once the network load becomes lower, the conventional cooperation-assisted scheme becomes more energy efficient regardless of the radio link quality, indicating that the load parameter q has greater impact to the cooperation-assisted scheme compared to the link quality. The reason for this is that, while the network load conditions affect all aspects of the cooperation scheme, the effect of parameter p is more limited, since no scanning is made before querying a candidate network for resources. Therefore p has no impact in the association attempt to networks discovered through short-range cooperation.

VI. CONCLUSIONS

The paper introduced the concept of short-range cooperation for energy efficient vertical handovers and developed a model for capturing the associated mean energy expenditure per handover by means of closed-form expressions. The model encapsulated various important cooperation and handover-related parameters and allowed the comparison of cooperation-assisted VHOs to the conventional handover scheme.

Simulation results validated the proposed analytical model and highlighted the energy efficiency benefits of the proposed scheme in various realistic scenarios. Additional aspects of the cooperation mechanism were evaluated through the analytical model and the effect of various relevant factors was studied; results indicate network availability, radio link conditions in the local area and network loading conditions in candidate networks to be the key influencing factors. Overall the results show that the proposed cooperation scheme outperforms the conventional approach in terms of energy efficiency in several realistic usage scenarios.

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