Localization and Mobility Management in Heterogeneous Wireless Networks with Network-Assistance

Dionysis Xenakis

National and Kapodistrian University of Athens
Department of Informatics and Telecommunications
`nio@di.uoa.gr`

Abstract. Today's heterogeneous wireless network (HWN) is a collection of ubiquitous wireless networking elements (WNEs) that support diverse functional capabilities and networking purposes. In such a heterogeneous networking environment, localization and mobility management will play a key role for the seamless support of emerging applications, such as social networking, massive multiplayer online gaming, device-to-device (D2D) communications, smart metering, first-responder communications, and unsupervised navigation of communication-aware robotic nodes. Most of the existing wireless networking technologies enable the WNEs to assess their current radio status and directly (or indirectly) estimate their relative distance and angle with respect to other WNEs of the same Radio Access Technology (RAT); thus, the integration of such information from the ubiquitous WNEs arises as a natural solution for robustly handling localization between WNEs and mobility management of moving WNEs governed by resource-constrained operation. Under this viewpoint, we investigate how the utilization of such spatial information can be used to enhance the performance of localization and mobility management in the today's HWN. In this work we focus and contribute in the areas of: i) localization and peer-discovery between non-homogeneous WNEs, ii) network-assisted D2D discovery in cellular networks, iii) energy-efficient handover (HO) decision in the macrocell - femtocell network, and iv) network-assisted vertical handover decision (VHO) for the integrated cellular and WLAN HWN.

Keywords: Localization, Peer-to-peer discovery, Handover, Heterogeneous Wireless Networks, Device-to-Device Discovery, Femtocells.

1 Dissertation Summary

1.1 Introduction

Over the past few years, wireless networks have transformed from a set of single-tier operator-deployed circuit-switched systems, designed to support voice-centric services in wide geographical regions, to a set of multi-tier networking

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[1] Dissertation Advisor: Lazaros Merakos, Professor

clusters of user-installed IP-based wireless networking elements (WNEs), designed to support heterogeneous communication capabilities and diverse networking requirements. The nowadays heterogeneous wireless network (HWN) is composed by tower-mounted cellular base stations (BSs) providing wide area coverage (a.k.a. macrocells), user-deployed low-power and small-sized base stations that boost the area spectral efficiency of the licensed spectrum [1] (e.g. femtocells), wireless local area network (WLAN) stations that enable high-data rate connections to the Internet over the unlicensed spectrum [2], as well as other low-cost low-power and battery-operated sensors that monitor, measure, and commute localized changes in nearby sink nodes (e.g. in the smart grid).

In such a heterogeneous wireless networking environment, the mobile terminals (or the WNEs) are required to discover the set of nearby WNEs that they can access and, if needed, to seamlessly transfer their ongoing services by associating with the one(s) that meet their particular communication requirements. Even though different terms are used among the different systems for the discovery, e.g. network discovery in IEEE-based systems or cell search in 3GPP-systems, and the association phase, e.g. handover for intra-system mobility in cellular systems and vertical handover for inter-system mobility in heterogeneous systems, the discovery and association phases are integral part of the mobility management (MM) process of all the existing wireless networking technologies.

Since the nowadays mobile terminals are equipped with numerous radio access interfaces, that enable them to access the Internet via multiple Radio Access Technologies (RATs), mobility management is a challenging issue for safeguarding the robustness of the nowadays HWN. Firstly, the support of multiple radio interfaces asks for increased complexity and battery consumption at the mobile terminal, due to the substantially increased number of (not necessarily homogeneous) WNEs that should be discovered and evaluated with respect to their ability to support the service requirements of the mobile terminal. Secondly, the recent surge of interest for the direct exchange of localized traffic between nearby devices without network involvement, a.k.a. peer-to-peer (P2P) communications, questions the scalability of the predominant user-assisted network-controlled mobility management model that is currently adopted by the vast majority of cellular networks. Social networking applications, massive multiplayer online gaming, device-to-device (D2D) communications, smart metering, first-responder communications, and unsupervised navigation of communication-aware robotic nodes, are only some of the emerging applications that motivate this disruptive communication paradigm [3][4][5]. Thirdly, the nowadays HWN is characterized by the unplanned deployment of densely overlapping (in coverage) WNEs that serve diverse communication purposes over the same spectrum. This feature not only dictates the employment of semi-autonomous terminal-based discovery, but also transforms the nowadays HWN to a stochastic system dominated by the spatial dependencies of the heterogeneous WNEs.

Aiming to improve the mobility, interference, and energy management at the WNEs, more and more wireless networking technologies incorporate a suite of measurement capabilities to their baseline operation. Such measurements enable the fixed (or moving) WNEs to assess the status of the ambient radio environment, e.g. interference level in a specific spectrum band, and directly (or indirectly) estimate their physical distance and angle with respect to other WNEs of the same RAT. The incorporation of knowledge on the radio status or the spatial dependencies between the WNEs, arises as the natural solution for effectively handling the unplanned and overlapping deployment of WNEs upon mobility management. The integration of such spatial information can also be the cornerstone for more accurate localization between WNEs that do not necessarily support the same RAT, i.e. heterogeneous WNEs. Besides, localization, which refers to the process by which a WNE estimates its physical distance (or connectivity) to another WNE, is currently considered as a vital component in the future 5G network where the estimation of proximity between the myriads of WNEs can be a limiting performance factor [6].

Under this viewpoint, in this doctoral thesis we investigate how knowledge of the radio status or the spatial distribution of the WNEs can be used to enhance the performance of localization, discovery, and association in the nowadays HWN. Besides, the exploitation of such spatial information is the common denominator for all algorithms and analytical models developed in this work. The remainder of this section is organized as follows. In section 1.1, we start with an illustrative example that motivates the utilization of radio/positioning measurements from the heterogeneous WNEs as means of improving the performance of localization, discovery, and association in the nowadays HWN. In section 1.2, we briefly summarize related works and our key contributions in the areas of localization and peer-discovery in HWN, device-to-device discovery in cellular network, energy-efficient handover decision in the macrocell - femtocell network, energy-efficient vertical handover decision in the cellular/Wi-Fi network, and mobility management in the LTE-Advanced Network with Femtocells.

1.2 Motivating Example and Research Areas

In Figure 1 we depict an instance of the nowadays HWN, which is composed by long-range cellular BSs, e.g. macrocells, numerous small-sized stations that operate in the licensed spectrum, e.g. picocells or femtocells, WLAN access points that operate in the unlicensed spectrum, e.g. Wi-Fi hotspots, dual-mode cellular/Wi-Fi hotspots (fourth generation (4G) hotspots), low-power sensors, e.g. ZigBee sensors, localized traffic aggregators/sink nodes, e.g. dual-mode Wi-Fi/ZigBee smart meters, D2D-enabled cellular devices, and communication-enabled robotic nodes, e.g. dual-mode Wi-Fi/cellular robots. To better comprehend the key research areas of this work, consider the scenario where the dual-mode robot (source peer) seeks to discover a malfunctioning ZigBee sensor (target peer) to replace it. The dual-mode robot is assumed to host active connections to the Internet. Firstly, the communication-enabled robot is required to (continuously re-)assess its physical distance to the malfunctioning ZigBee sensor by employing localization, i.e. estimate the distance Z1. Secondly, as the robot moves towards the malfunctioning ZigBee sensor, at some point it will have to choose between associating with Femto 1 (femtocell) or BS 2 (macrocell), which refers to the scenario of intra-system mobility in the macrocell-femtocell network, i.e. horizontal handover. In the sequel, the robot will have to choose between associating with Femto 2 (femtocell), Wi-Fi 2 (WLAN access point), BS 2 (macrocell) or BS 1 (macrocell), which refers to the scenario of inter-system mobility between heterogeneous RATs, i.e. vertical handover. Since the robot is a battery-operated device, its ongoing services should be seamlessly transferred to the WNE that not only guarantees a prescribed Quality of Service (QoS) target, but also requires the minimum energy consumption overhead for communications, i.e. need for energy-efficient horizontal or vertical handovers. Finally, assuming that the ZigBee sensor (Sensor 1) is located in a difficult to access area, the dual-mode robot is required to discover a local D2D-enabled device (User 1) that will be responsible for remotely navigating the robot by exploiting visual signal from its on-board camera (localized real-time video traffic).

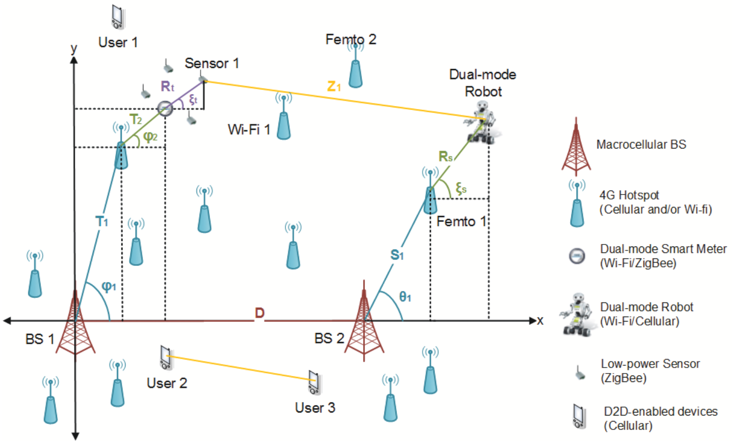

Fig. 1. Motivating example for localization and mobility management in wireless heterogeneous networks using network-assistance

Aiming to cover the first challenge, which refers to the localization between not necessarily homogeneous WNEs over large geographical areas, e.g. the robot and the ZigBee sensor, in this work we analyze how partial or full knowledge on the spatial dependencies between the nodes, e.g. relative distances and angles with respect to a reference direction, affect the localization precision and the peer discovery accuracy in the nowadays multi-tier clustered HWN. On the other hand, aiming to cover the challenge of energy-efficient horizontal handover in the macrocell - femtocell network, we propose an energy-efficient handover algorithm that exploits standard measurements on the radio status of nearby base stations (femtocells or macrocells) to identify the one that minimizes the transmit power at the mobile terminal given a prescribed mean Signal to Interference plus Noise Ratio (SINR) target (QoS indicator). To address the challenging issue of energy-efficient network selection between cellular and WLAN WNEs, we propose an energy-efficient vertical handover algorithm that utilizes standard measurements on the radio status of nearby base stations or WLAN access points, in order to identify the point of attachment (PoA) that minimizes the power consumption at the mobile terminal given a prescribed mean SINR (QoS indicator). Finally, we also analyze how different combinations of location information on the cellular network layout can be used to enhance the performance of network-assisted D2D discovery. We note that even though we use the example in Figure 1 to allow a more easy understanding of the research areas addressed in this work, the proposed analytical models and algorithms apply to more generic scenarios and deployment layouts.

1.3 Related Works and Key Contributions

Localization and Peer-Discovery in Heterogeneous Wireless Networks Localization poses several challenges that span from mitigating (or exploiting) prominent effects of the wireless medium [5] [7] to employing multi-user detection (MUD) and cooperation for more accurate localization [8]. The Poisson point process (PPP) has been recently shown to be as accurate as the grid model and a good fit for modeling the locations of small-sized stations in multi-tier cellular networks with independent tiers [1]. Besides, the PPP model has been used to derive near-optimal strategies for random peer discovery in homogeneous networks [9]. In parallel, a considerable amount of works identify that the locations of short-range WNEs are not completely random, e.g. sensors, femtocells, or more generic WNEs [10][11], and typically form clusters around other WNEs of increased radii.

In our work, we derive closed-form expressions for the conditional probability distribution of the distance between two heterogeneous WNEs, given partial knowledge of the spatial relations between their upper-tier parent WNEs. We also show that the probability density function (pdf) expressions describe the statistical behavior of localization between heterogeneous WNEs. Moreover, we analyze the performance of location-aware peer discovery between heterogeneous WNEs given different knowledge of the HWN layout. We also analyze the impact of the key system parameters on the performance of location-aware peer discovery and derive optimal strategies for the placement of upper-tier WNEs as means of maximizing the peer discovery probability between two heterogeneous WNEs of interest. We conclude with valuable insights for the design of location-aware peer discovery in the today's HWN.

Device-to-Device Discovery in Cellular Networks Most of the related literature to our work deals with the analysis and optimization of D2D communications [12]. In parallel, PPPs, which have been extensively used for the analysis of multi-tier cellular networks [1], are increasingly used to model and analyze the performance of D2D communications [13]. Our work addresses the challenging issue of network-assisted D2D discovery in random spatial networks. Our key contributions can be summarized as follows. Firstly, we derive closed-form expressions for the conditional pdf and ccdf of the distance between two

D2D peers, given various combinations of location information parameters including at least the distance or the neighboring degree between their associated BSs. Secondly, we analyze the performance of network-assisted D2D discovery given the most prominent combinations of location information parameters. Our analysis readily quantifies how different levels of location knowledge affect the D2D discovery probability. Thirdly, we examine the behavior of the D2D discovery probability with respect to key system parameters, with the emphasis given on the BS density. We identify conditions under which the D2D discovery is optimized and provide analytical expressions for computing the optimal BS density. Finally, we provide useful design guidelines for network-assisted D2D discovery in cellular networks.

Handover Decision in the Macrocell - Femtocell Network Current literature also includes various algorithms and studies for the HO decision phase in the two-tier network [14]. However, current HO decision algorithms emphasize on reducing the number of HOs in the two-tier network mainly based on user mobility and traffic type criteria. In most of the cases, the impact of the proposed algorithms on the UE energy consumption, the RF interference, and the network signaling load, is not investigated.

In our work, we jointly consider the impact of interference, energy consumption, and user mobility during the HO decision phase in the two-tier LTE-A network. A strong innovation of our work is the exchange and utilization of standard LTE-A measurements to accurately estimate the mean UE transmit power on a per candidate cell basis, given a prescribed mean SINR target. The exclusion of candidate LTE-A cells which can compromise wireless connectivity, and the incorporation of the user's prescribed SINR target during the mean UE transmit power estimation, are two more important features of the proposed algorithm towards sustained wireless connectivity, enhanced QoS support, and reduced outage probability. We also provide comprehensive description of the network signaling procedure required for employing the proposed algorithm.

Energy-Efficient Vertical Handover Decision in the Cellular / Wi-Fi network Current literature includes a noteworthy amount of algorithms for horizontal and vertical handover decision for heterogeneous networks [14][15]. However, only a few works utilize the ANDSF functionality for efficient network discovery and seamless mobility at the MMT. In addition, even though the utilization of standard LTE-A measurements for handover has been recently proposed [16], the joint utilization of the enhanced radio measurement capabilities of the LTE-A and the IEEE 802.11-2012 systems is an unexplored research area [17]. In our work, we propose an Andsf-assisted eneRgy-effiCient vertical Handover decisiON (ARCHON) algorithm for the heterogeneous IEEE 802.11-2012 / LTE-A network. The proposed algorithm, referred to as ARCHON, enables a MMT to select the network PoA that minimizes its average overall power consumption and guarantees a mean SINR target for its ongoing connections.

Mobility Management in the LTE-Advanced Network with Femtocells Current literature lacks of surveys and comparative studies engaged with the matter. In our work, we discuss the open issues for MM support in the presence of femtocells and overview the key aspects of MM in the LTE-A system. Moreover, we survey current state-of-the-art HO decision algorithms for the two-tier macrocell-femtocell network and overview their key features, main advantages and disadvantages under the viewpoint of the LTE-A system. We also evaluate the performance of the most prominent current state-of-the-art algorithms by providing both qualitative and quantitative comparisons by using the Small Cell Forum evaluation methodology.

2 Results and Discussion

In this section, we briefly introduce the system model (section 3.1), one of our main theorems (section 3.2), and a key result (section 3.3) of our work in the area of Localization and Peer Discovery in Heterogeneous Wireless Networks with location-assistance.

2.1 System Model

We consider a fairly general HWN of M tiers, where each tier consists of WNEs that serve similar communication purposes and support the same RAT. The WNEs belonging to the m-th tier are referred to as tier-m WNEs ($m = 1, \dots, M$). We consider that the tier-1 WNEs form a homogeneous PPP Φ_1 with intensity λ in the Euclidean plane, e.g. medium to long range base stations, and that, for $m > 1$, the tier-m WNEs are clustered around *some of* the tier-($m-1$) WNEs. We emphasize on around *some of* and *not all* tier-($m-1$) WNEs, since in practical deployments we do not expect a tier-m cluster around every tier-($m-1$) WNE. Let Φ_m denote the complete point process (PP) of tier-m WNEs, i.e. the union of all tier-m clusters. Given that a tier-m cluster is present around the tier-($m-1$) WNE $v_i \in \Phi_{(m-1)}$, we assume it to be in the form $N_{v_i}^m = N_i^m + v_i$, where the point sets N_i^m are independently and identically distributed (i.i.d) and independent of the parent PP Φ_{m-1}. All tier-m clusters are modeled by the Thomas cluster process as follows [11]: a) the number of points in each tier-m cluster is Poisson distributed with mean $\bar{c}_m$, and b) the WNEs in a tier-m cluster are scattered independently according to a symmetric normal distribution around the parent tier-($m-1$) WNE with variance σ_m^2.

We now turn our attention to the two WNEs of interest, coined as *source* and *target* peers. We consider that the source peer associates with a tier-m_s WNE, coined as the *associated WNE of the source peer*, and that the target peer associates with a tier-m_t WNE, coined as the *associated WNE of the target peer*. The associated WNEs of the two peers can belong to different tiers in the HWN. Accordingly, the two peers do not necessarily support the same RAT. We assume that the source and the target peers are located around their associated WNEs according to a symmetric normal distribution with variances σ_s^2 and

Table 1. Location Information Parameters (Spatial Information)

Parameter	**Notation**	**Comments**
Inter-site distance between the tier-1 parent WNEs of the peers	D	Can be estimated by performing TD or RSRP measurements between the tier-1 parent WNEs of the two peers.
Neighboring degree between the tier-1 parent WNEs of the peers	k	Can be estimated in a similar manner with D (lower accuracy is required).
Distance between the source peer and its associated WNE	R_s	Can be estimated by performing TD, ToA, RSS, or RF power level, either at the source peer or its associated WNE.
Angle between the source peer and its associated WNE	ξ_s	Can be estimated by performing AoA measurements or by employing other indirect estimation methodologies depending on the RAT.
Distance between the target peer and its associated WNE	R_t	Can be estimated in a similar manner with R_s.
Angle between the target peer and its associated WNE	ξ_t	Can be estimated in a similar manner with ξ_s.
Distance between the tier-m and the tier-*(m-1)* parent WNEs of the source peer	S_{m-1}	Can be estimated by performing TD, ToA, RSS, or RF, either at the tier-m parent WNE or at the tier-*(m-1)* parent WNE, depending on the RAT.
Angle between the tier-m and the tier-*(m-1)* parent WNEs of the source peer	θ_{m-1}	Can be estimated in a similar manner with ξ_s, depending on the RAT. It is assumed to be measured with respect to the reference direction from the tier-1 parent of the source peer to the tier-1 parent of the target peer.
Distance between the tier-m and the tier-*(m-1)* parent WNEs of the target peer	T_{m-1}	Can be estimated in a similar manner with S_{m-1}.
Angle between the tier-m and the tier-*(m-1)* parent WNEs of the target peer	ϕ_{m-1}	Can be estimated in a similar manner with ξ_s. Measured with respect to the reference direction from the tier-1 parent of the source peer to the tier-1 parent of the target peer.

σ_t^2, respectively. The locations of the two peers are assumed to be mutually independent and independent of the locations of other WNEs.

Since we are interested on analyzing how different levels of location-awareness affect the performance of localization and peer discovery in HWNs, we assume the presence of a location information server (LIS) that maintains some basic knowledge of the HWN layout. We assume that the LIS is aware of the clustering relations between the WNEs and capable of identifying the parent WNEs of both peers up to tier-1. For brevity, we refer to the tier-m WNE in the sequence of parent WNEs for the source peer as the *tier-m parent of the source peer* ($m < m_s$), and use a similar terminology for the parents of the target peer ($m < m_t$).

Aiming to capture the different levels of location-awareness that the LIS can provide to the peers, we consider it capable of utilizing spatial information on the relative distance and angle between two tagged WNEs of interest. In Table 1, we list the spatial information considered in this paper and provide insights on how they can be estimated in existing systems. In the sequel, we denote by $\mathcal{L}_s$ and $\mathcal{L}_t$ the set of parent WNEs of the source and the target peer, respectively, for which the LIS has knowledge of their relative polar coordinates with respect to their upper-tier parent WNEs. The remainder set of parent WNEs are denoted by $\not{\mathcal{L}}_s$ and $\not{\mathcal{L}}_t$, respectively. Fig. 1 depicts all parameters and random variables (RVs) involved in our analysis.

Since the performance of localization and peer discovery is tightly coupled with the definition of proximity between the WNEs of interest, we define the peer discovery probability as follows:

$$\mathcal{A}_{\mathcal{J}} = P\left[Z \leq \left(\frac{c}{Z_{th}} \right)^{\frac{1}{a}} \middle| \mathcal{J} \right], \tag{1}$$

where $\mathcal{J}$ denotes the available knowledge of the HWN topology, c is a scaling factor, a is a decay exponent, Z is the distance between the two peers, and Z_{th} is a fixed threshold that guarantees proximity between the two peers.

2.2 Main Result

Theorem 1. *The conditional pdf $f_{Z|D}(z)$ of the distance Z between the source and the target WNEs in a multi-tier clustered random HWN, given a) the distance D between their tier-1 parent WNEs and b) the relative polar coordinates of their parent WNEs in $\mathcal{L}_s$ and $\mathcal{L}_t$, is given by*

$$f_{Z|D}(z) = \frac{z}{\sigma^2} e^{-\frac{\eta_x^2 + \eta_y^2 + z^2}{2\sigma^2}} I_0 \left[\frac{z\sqrt{\eta_x^2 + \eta_y^2}}{\sigma^2} \right], \tag{2}$$

where $I_0[x]$ is the modified Bessel function and the parameters η_x, η_y, and σ are given by:

$$\eta_x = D + \sum_{j \in \mathcal{L}_s} S_j \cos\phi_j - \sum_{i \in \mathcal{L}_t} T_i \cos\theta_i, \tag{3}$$

$$\eta_y = \sum_{i\in\mathcal{L}_t} T_i \sin\theta_i - \sum_{j\in\mathcal{L}_s} S_j \sin\phi_j, \tag{4}$$

$$\sigma^2 = \sum_{j\in\not{\mathcal{L}}_s} \sigma_j^2 + \sigma_s^2 + \sum_{i\in\not{\mathcal{L}}_t} \sigma_i^2 + \sigma_t^2. \tag{5}$$

The corresponding ccdf $\bar{F}_{Z|D}(z)$ *is given by*

$$\bar{F}_{Z|D}(z) = Q_1\left[\frac{\sqrt{\eta_x^2+\eta_y^2}}{\sigma}, \frac{z}{\sigma}\right], \tag{6}$$

where $Q_1[a,b]$ *is the Marcum-Q function of the first order. If the relative polar coordinates* (R_s,ξ_s) *of the source peer and/or* (R_t,ξ_t) *of the target peer are also given, (2) and (6) hold with* η_x*,* η_y*, and* σ*, as given in the PhD dissertation.*

Theorem 1 can be used to analytically evaluate the peer discovery probability between two WNEs (1), given any combination of spatial information that includes the distance D. The requirement of knowing D can be readily met in practical HWNs, where the locations of tier-1 WNEs typically remain fixed over time. The results in Theorem 1 not only allow heterogeneous WNEs to handle the uncertainty on their proximity, but also enable them to employ different levels of location-awareness upon localization or peer discovery depending on the available spatial information.

2.3 On the Impact of Angles between the WNEs

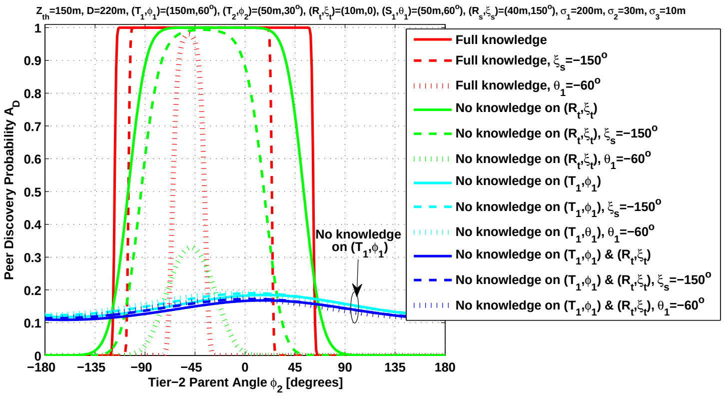

Fig. 2. Peer Discovery Probability given D vs. Tier-2 Parent Angle ϕ_2 [degrees]

The employment of accurate AoA measurements increases the complexity and processing requirements for the radio transceiver. With this in mind, in Fig.

2 we investigate the impact of the ϕ_2 angle between the tier-3 and the tier-2 parents of the target peer on the probability $\mathcal{A}_D$. As expected, when the LIS has full knowledge on the locations of the peers and their parent WNEs, the peer discovery can be either successful or not. Notably, there exists a ϕ_2 interval within which the peer discovery remains roughly unaffected. This interval is shown to be expanded, shifted, or compressed, in relation with the rest of the parameters governing the HWN topology. For example, if the angle ξ_t between the target peer and its parent tier-3 WNE is equal to -150^o (instead of 150^o), then the ϕ_2 interval for successful peer discovery is compressed and shifted to the left (red dashed line in Fig. 2. This effect is due the fact that for $\theta_2 = -150^o$ the two peers are separated by a higher distance. Even more evident is the compression of the ϕ_2 interval when the angle between the tier-1 and tier-2 parent WNEs of the source peer is set to $\theta_1 = -60^o$ instead of ($\theta_1 = 60^o$) (red dotted line), since the distance between them is even higher. Such an effect is also expected in the nowadays HWN, where the distance between WNEs in higher tiers is (on the average) higher compared to the one between lower-tier WNEs.

Interestingly, a similar interval exists when the LIS is not aware of the relative coordinates of the target peer (green lines). Notice that the lack of such information prolongs the tail of the respective ϕ_2 interval with full knowledge in both directions. When the LIS has no knowledge of the coordinates (T_1, θ_1) of the tier-2 parent WNE, the probability $\mathcal{A}_D$ is shown to remain roughly unaffected by the values of ϕ_2 (blue and cyan lines). This relation indicates that the benefits from performing accurate measurements on the angles between low-tier WNEs are marginal when the relative coordinates of high-tier parent WNEs are not known to the LIS.

From the discussion above, we draw two important design guidelines. Firstly, the accurate estimation of the angle between low-tier WNEs and their parent WNEs is necessary only when an accurate estimation is required, e.g. the proximity threshold is low. Secondly, depending on the available spatial information, the low-tier WNEs can relax the accuracy of AoA measurements without significantly deteriorating the performance of peer discovery.

3 Conclusions

More and more WNEs are capable of estimating their radio-status as well as their relative position with respect to other nearby WNEs of the same technology. Integrating such spatial information from the ubiquitous WNEs of different RATs, is a key enabler for fine-grained localization and mobility management between the myriads of WNEs. In our work, we have investigated how knowledge of the radio status or the spatial distribution of the WNEs can be used to enhance the performance of localization, peer discovery, and association in the nowadays HWN. Our key contributions lie in the areas of localization and peer-discovery in HWN, device-to-device discovery in cellular network, energy-efficient handover decision in the macrocell - femtocell network, energy-efficient vertical handover decision in the cellular/Wi-Fi network, and mobility management in the LTE-Advanced Network with Femtocells. We have provided both analytical and simulation means to evaluate the performance of the proposed frameworks, models, and algorithms.

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