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Context-based wireless mesh networks: a case for network virtualization

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Abstract Wireless Mesh Networks (WMNs) have gained increasing attention as an attractive means to provide connectivity in complement to access as offered by regular Internet Service Providers (ISPs). Such a grass-root technique, however, often suffers from detrimental operating conditions and poor quality. Network virtualization, on the other hand, has been widely advocated as a possibility to overcome what has often been referred to as the ossification of the Internet. Combining the concept of network virtualization with WMN technology, therefore, appears to be promising and desirable. It is envisioned that well managed multiple Virtual Networks (VNs) may overcome shortcomings of WMNs on the one hand, and extend the reach of the Internet beyond its current confinement into the realm and control of the user on the other hand. In this paper, we argue for a context-based approach for an effective means to extend multi-VNs from the Internet domain into WMN environments. We describe both mobility and preferences as *context models* in order to create virtualized WMNs based on these types of context models. As a result, it is envisioned to achieve a comprehensive connectivity coverage, accompanied by high assurance in network quality. We further present a distributed solution to manage multi-VNs, and a mobility-aware context use case to demonstrate the usefulness of our approach.

Keywords Wireless mesh networks · Network virtualization · Context · Management and control · Mobility prediction

1 Introduction

Wireless Mesh Networks (WMNs) are spreading both in city and rural areas to connect heterogeneous home users. Their aim is to support (mobile) users seamlessly with cheap and easy to maintain connectivity. The mesh topology of WMNs provides high flexibility as mesh routers are connected with multiple others providing the physical infrastructure for flexible routing and transport connections. Network virtualization can make use of this mesh topology by sharing, and also by combining links for desired network properties.

Context information can be used to autonomously build logical, virtual networks (overlays) on top of physical networks in order to support transport optimization based on context information; these context-based networks can be used to connect the users that share the same interests, mod-

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eled as context information, and request similar services. Hereby, network virtualization can be very useful for a flexible utilization of a network infrastructure by enabling the parallel use of the same infrastructure for different networks.

In our approach, we model networking relevant user *context*, i.e., QoS, security, user mobility, cost, etc., and virtualize the WMNs by introducing multiple Virtual Networks (VNs) to represent the context characteristics. In this scheme, the users connect to the VN that best fits their context requirements, taking into account both user and services requirements. The VNs are configured and updated with respect to the users and service context requirements. To demonstrate the impact of context, we selected *mobility* out of the set of possible characteristics and describe the impact and use of information about mobility in our approach. Mobility context has been selected, because of its clear impact on networking, like on connectivity, handover, and topology management. Movement can be characterized along different features like speed, direction, frequency of direction changes, etc. In our scenarios, we assume continuous movement and focus on speed as one of the important characteristics resulting in different handover frequencies in the mesh network which directly affects the creation and user assignment to a VN. In our analytical evaluation of delays caused by virtual network selection and configuration, we demonstrate how the number of VNs and the nodes per VN influence delays and how mobility prediction can decrease these delays for discovery and reconfiguration of VNs.

The paper is organized as follows. Section 2 introduces WMNs and their specific properties. Section 3 gives an overview of related work concerning context-aware networking, multi-virtual networking, and their application to WMNs. Section 4 introduces the concept of user context-aware multi-VN based organization of WMNs together with the proposed architecture, followed by Sect. 5, where a possible distributed solution for context-based characterization and management of VNs is presented. We analytically evaluate the delays involved in the context-aware management approach in Sect. 6 by introducing a mobility-awareness context use case that is supported by a user mobility prediction mechanism. Finally, Sect. 7 concludes the paper.

2 Wireless mesh networks characteristics

The particular characteristics of WMNs [1] are derived from the (mesh) topology and the dynamics of wireless environments. Instead of being another type of ad-hoc network, WMNs diversify the capabilities of ad-hoc networks, presenting low up-front costs, easy network maintenance, robustness, reliable service coverage, and minimal mobility of mesh routers. In addition to being widely accepted in the traditional application sectors of ad-hoc networks, WMNs are thus undergoing rapid commercialization in many other application scenarios, such as broadband home networking, community networking, building automation, and Internet access particularly in rural areas. At the same time, WMNs are already being used in free wireless access initiatives, like funkfeuer[1] and freifunk[2] based on IEEE 802.11 technology.

Nevertheless, the distinct characteristics of WMNs, setting them apart from traditional wireless networks, bring up new challenges to communication protocols, network management, reliability assurance, and security [1]. Scalability, for instance, has been identified as a major problem of important WMN protocols, but there are other open issues, such as the support of multicast applications and the utilization of multi-radios and multi-channels. In particular, the characteristics of the nodes have to be considered in the routing protocols since they can no longer be assumed to be similar.

Considering the different contextual features and preferences of the users in current WMN environments, the users need to be linked to different wireless access networks with different bandwidth and robustness features, probably belonging to different Internet Service Providers (ISPs) with different security policies. The customers use different devices with different capabilities, which run different applications with different QoS requirements. As WMNs are edge networks connecting (mobile) users, they are expected to play an important role when introducing the required context-based user-centric networks. Moreover, WMNs are adaptable, self-configuring, and self-organizing to a high degree. As a consequence, WMNs are well suited to demonstrate the benefit of context-based approaches considering heterogeneous node capabilities and user preferences.

3 Related work

In this section, we describe selected related work and projects that address context-awareness and virtualization, with particular emphasis on their application to WMNs.

3.1 Context-aware networks

Context-aware overlay networks have been previously proposed for ambient networks [2], where context is derived based on sensor readings. In [3–6], the authors present a self-management approach to create, configure, adapt, contextualize, and finally teardown specific context-aware overlay networks, which enable the composition and delivery of services to the end-users. The service overlay networks are structured and reconfigured according to the changes of the user and network context in a self-adaptive manner.

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[1] http://www.funkfeuer.at/.

[2] http://www.freifunk.net/.

In [7, 8], a policy layer is proposed for the management (creation, termination, adaptation to the changing conditions of the environment) of context-aware overlay networks, where overlays are built based on user context, network and service providers.

In [9], the authors present a context-aware architecture for multi-party sessions and network control (C-CAST project[3]) which dynamically adapts to context changing and maintains the connectivity with the expected requirements over session lifetime. The concepts of dynamic sessions and network control driven by context are considered, and the architecture introduces the concept of abstract trees in the network to increase the stability of the network to any context change.

3.2 Multiple virtual networks

There are several approaches that deal with building up several VNs over the same physical network. Physical routers, switches, or interfaces are thereby virtualized in order to construct VNs on top of a physical network connecting several virtual instances. Each of these VNs shares the resources from different infrastructure providers, running their own services and protocols in parallel, with the level of transparency and isolation required.

Among other projects, PlanetLab [10] allows the slicing of a large-scale overlay testbed into different VNs (or slices), in order to design, evaluate, and deploy geographically distributed network services. Management services are also in place to control the entire overlay, which runs on their own slices. VINI [11] is an extension of PlanetLab which uses its infrastructure. It can be considered as a specific instantiation of an overlay network that runs software routers and allows multiple VNs to exist in parallel. The incorporation of programmability in PlanetLab allows users to evaluate their own protocols and services in real environments.

GENI [12] presents many similarities to PlanetLab. It provides an open and large-scale testbed to evaluate new architectures by creating customized VNs, carrying real traffic on behalf of end-users, and connecting to the existing Internet to reach external sites. Similar to PlanetLab, it includes sliceability to isolate and share resources spatially and temporally, and a flexible platform for users' access in order to test and evaluate their own proposals.

CABO [13] is a network virtualization approach that provides separation between infrastructure and service providers, offering the possibility of running end-to-end services over equipment owned by different infrastructure providers. CABO gives service providers direct control over the protocols and services that run on the virtual nodes, and allows them to instantiate a VN on a multi-provider infrastructure. In addition, it enables infrastructure providers to automatically discover and manage their infrastructure.

3.3 Context-aware wireless mesh networks

So far, research on context-awareness in WMNs has mainly concentrated on Quality of Service (QoS)-aware routing mechanisms. Many routing schemes consider the quality of communication links by integrating signal interference measures into their metrics, like proposed in [14]. An architecture which adapts to current network conditions (determined by performance metrics and history data) for the support of real-time communication is proposed in [15]. The robustness of paths is determined by metrics for availability, bandwidth, delay, and outages based on network monitoring and statistical evaluation. In [16], a rule-based middleware for context adaptive routing in WMNs is described. Here, routing metrics, like hop count, retransmission count, and link interference, are related with context data, i.e., security level, traffic priority, and mobility, by means of manually configured rules. Based on neural networks, such relations can be learned from past experiences, as described in [17] for user mobility.

Approaches to WMNs particularly aware of the mobility of mesh clients can be found in [18–20]. In [18], an adaptive routing algorithm is proposed, which reacts to the intensity of mobility within the WMN. It is assumed that the mobility in the network can be determined to be high if link breakages are detected. Depending on the mobility assumed, either a reactive or a proactive routing algorithm is applied. The current position of mesh clients is taken into account by channel assignment and router selection in the work proposed in [19]. In particular, the position information is used by channel assignment and router selection algorithms adapting to significant location changes of clients. In [20], the authors present two mobility-aware clustering schemes that aim at improving the radio resource utilization in WMNs where the mesh network is divided into virtual clusters in order to restrict the majority of signaling messages to a local area. In the static clustering scheme, the optimal cluster placement is determined by using a linear-programming-based method to minimize resource utilization costs, whereas the second, less time-consuming clustering algorithm optimizes the cluster placement in a distributed manner. Additionally to the mobility-awareness aspect, these clustering schemes are related to our work insofar that the mesh clients are hereby also grouped "virtually".

Seamless connectivity is commonly achieved by handover mechanisms. Similarly for WMNs, there are several approaches to mobility management aiming at the support of seamless handover, which is also an objective of the architecture presented in this work [21–24]. In [21], a mesh

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[3] http://www.ictccast.eu/.

implementation is presented which targets fast handover on MAC and network layer based on a protocol modification of the Ad hoc On-Demand Distance Vector (AODV) routing protocol. During a handover, the route to a node moving from one router to another is rebuilt. TCP/UDP connections can thereby be maintained since the node's IP address is not changed. In [22], the authors describe a localized approach to mobility management and optimized post-handover routing. Here, users' location information is recorded on geographically close nodes. To maintain active connections during a handover, temporary routes are created and future handovers are prepared by means of routing control messages. In a similar way, the mobility support extension to proactive routing protocols presented in [23] uses neighbor client tables and a set of control messages to avoid packet loss during handover. An approach closely related to our virtual networks' concept is SMesh described in [24]. In order to support fast handover for real-time applications like VoIP, SMesh creates one virtual AP capable of serving all standard IEEE 802.11 devices. The handover of mobile clients is handled by one or more physical APs.

3.4 Virtualization in wireless mesh networks

This section presents several approaches that integrate network virtualization and overlay concepts to optimize the performance of WMNs.

Overlay networks, proposing "network slicing" over WMNs, are addressed in [25] to accommodate several experiments simultaneously in space, time, frequency division manner. In [26], the authors describe an approach of a joint optimization streaming rate allocation of traffic flows and power consumption of links for forwarding data flows in multicast overlays over WMNs. The streaming rate is adjusted in such a way that utility and network costs are optimized. In [27], a Wireless Ring (WRing) over a regular WMN is proposed in order to carry high bandwidth data, whereas in [28], MeshChord is presented, which uses location-dependent addressing schemes in order to reduce traffic for maintaining a Chord overlay [29] over WMNs.

In [30], the authors discuss the application of a cognitive radio overlay-based solution over WMNs capable of listing the surrounding wireless channel, making decisions on the fly, and encoding data using a variety of schemes in order to better explore the channel characteristics and to mitigate the interference.

In [31], the authors describe a Peer-to-Peer (P2P) overlay-based solution to locate the resources of the different available wireless networks. The overlay organizes wireless networks across traditional network operator, or technology boarders. Each peer stores a description and pointer to each resource indexed according to its geographic position and the range it covers. An application running on the mobile terminal accesses the P2P system, locates the wireless resources along a planned itinerary, and triggers handover at the lower layers (based on a pre-discovery of the wireless mesh topology using a context-aware search process).

3.5 Final remarks

The work presented in this section addresses topics in the area and demonstrates the importance of providing solutions to integrate context in WMNs. Our work extends related work by proposing an architecture addressing both context and virtualization in WMNs and the corresponding open research issues: (i) how to identify and rate context characteristics and automatically map them to a network structure (mapping multivariate context data to VNs); (ii) how to create an appropriate number of VNs; (iii) how to select the best fitting VN; and (iv) how to adapt and maintain the VNs in presence of context changes, dynamics of networks, and mobility of users.

4 Multi-VN architecture for context-based WMNs

Context is a driving characteristic of future user-centric Internet usage. Following the widely agreed definition of context in [32], context is understood to be any information that can be used to characterize the situation of an entity. Context characteristics of particular importance for networking are, e.g., location, mobility, privacy and security assurance, expected QoS, and pricing preferences. We provide a general model for a configurable set of context parameters, and select one parameter for demonstration purpose in the evaluation part, i.e., *mobility*. Along the context characteristics, the WMN is virtualized by creating multiple VNs in an autonomous manner (see also [33]) optimizing networking in a user-centric way. In our concept, mesh routers are network elements supporting the multiple VNs corresponding to different user-centric networks and solving potential conflicts. In that way, transport optimization will be supported by building specific VNs to group users sharing the same context and, consequently, to provide best fitting networks to the users.

To be able to provide an autonomic mapping function, the correlation of context characteristics to mesh network performance metrics has to be described and learned by the network. Based on the expected WMN performance, each VN can be setup and mapped to the physical network [34, 35]. Hereby, the current state as well as context prediction is considered. Furthermore, fuzzy context and trust in tracked context information can influence the decision to restructure a VN, or to assign users to a given VN. To solve these complex tasks, new mechanisms are required to create, maintain, and reconfigure the best VN for a specific user or set of users according to the context of all entities involved.

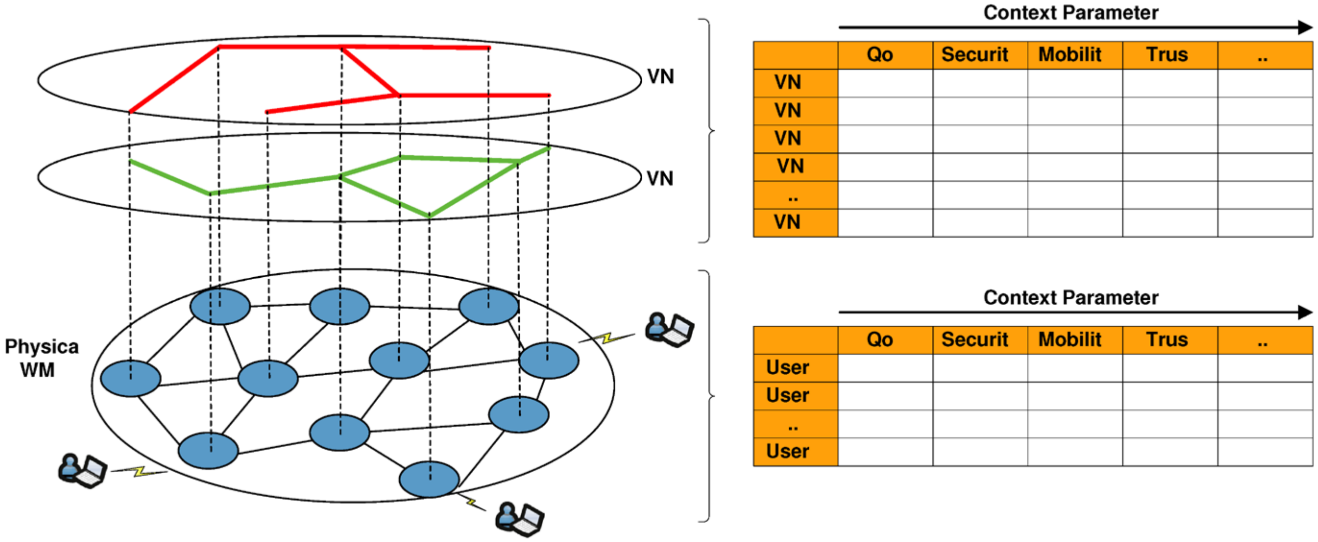

Fig. 1 Multi-VN architecture for context-based WMNs

A first sketch of our multi-VN architecture is shown in Fig. 1. Here, VNs are described by their multivariate properties as meta data. In principle, the number of context parameters is not limited but can be configured as required. Possible context parameters are QoS parameters, security levels, energy-efficiency metrics, and mobility metrics (important for mobility support and management). The n VNs resulting from the different classes of properties are used to abstract from and manage the underlying physical network. In this architecture, mechanisms to schedule resources, to manage user mobility, or to increase reliability and performance by using multi-homing techniques are considered. The following specific issues need to be addressed when implementing the proposed architecture, which will then be detailed in the following section:

Characterization of virtual networks: An important goal of our work is the characterization of each VN according to its context. The most important features of each VN and the context information should be efficiently distributed in the network, in order to provide fast lookup procedures of the best VN for specific user requirements.

Management of virtual networks: Intelligent algorithms are required to choose the best fitting VN for a specific user. It is an open issue how to create these multiple VNs that fit best the users and networks, with respect to efficiency (benefits related to the overhead required for managing the VNs) and overall quality enhancements.

An arbitrary selection of a VN (to which a node connects to) or of a set of concurrently used paths might even lead to interferences on different levels, e.g., with respect to radio interference or QoS values. Hence, more complex models including such dependencies are required.

Context modeling and prediction: In addition to introducing context-awareness to the network, the integration of context prediction allows to trigger management tasks in advance, pro-actively. In particular, mobility prediction can be used to select a VN based on a detected movement pattern, and can be used to start VN reconfiguration in advance, i.e., before the user roams to the next mesh router.

5 Implementation of the virtual network architecture

We aim at modeling context in a standardized form to be known by all network elements. Mapping of context information to VNs should be performed efficiently supported by fast discovery of virtual network elements for supporting the user's context characteristics. Hereby, the user's context characteristics and preferences can be modeled using ontologies capable to describe complex relations and dependencies, but also be based on simpler context levels. In our first modeling approach, we consider simpler context levels corresponding to the user's current situation.

Going one step further, whenever context information over time shows some regularities, these regularities can be learned by means of pattern recognition techniques and used to trigger management of VNs pro-actively. For example, user movement often shows regularities and this information can be used to restructure the VN to fit best to velocity impacts to mobility management and handover. Potential prediction techniques are known from time series analysis, n-order Markov models, clustering methods like Self-Organizing Maps (SOMs), Bayesian networks, etc.

Each node of the network supports several VNs, each of which representing a specific set of context information levels. With the vast amount of context information (and

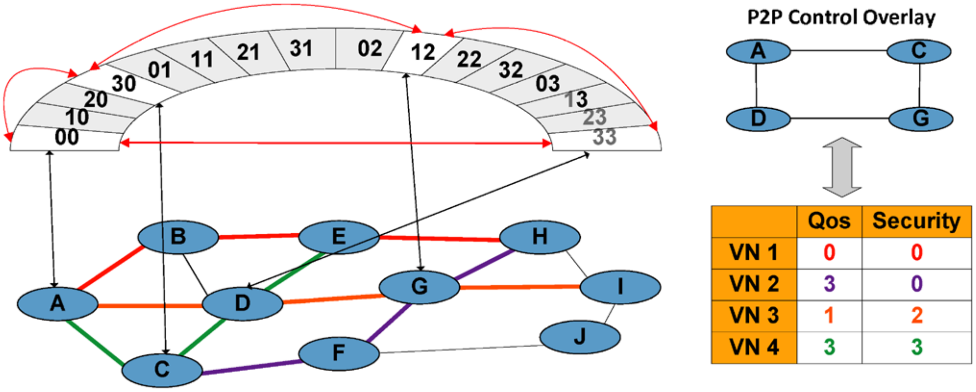

Fig. 2 Integrating context features of virtual networks

potentially, different VNs), it is important to provide efficient store, search, and mapping services. The services can be supported via centralized databases, where one element performs context management. However, centralized approaches have known limitations, such as limited scalability, leading to bottlenecks, and imposing single points of failure. In contrast, we consider a decentralized approach. Among other self-organizing and distributed architectures, a peer-to-peer based architecture provides preferable characteristics. Context information is distributed in the network and a distributed query mechanism performs the search. Hereby, structured peer-to-peer systems perform well for searching, in our case, for best-fitting VNs.

We detail our concept by presenting a possible approach to integrate context information into the network. First, we describe how VNs can be characterized in terms of context parameters; second, we detail the management of multi-VNs; finally, we exemplify our approach along the context characteristic *mobility*.

5.1 Characterization of virtual networks

We consider a network overlay to control the context-based architecture for WMNs [36]. The following solution can be used to characterize a VN, and to find the most suitable VN for a user:

1. Context features of each VN are organized in a P2P control overlay, i.e., in a ring in consecutive order of context levels. One node is chosen from each VN to represent the VN in the P2P control overlay.
2. A mechanism is introduced to create a key space efficiently which represents all types of context. Each key is used to describe a particular VN (or the user preferences). Then, a correct match of such key pairs is searched for. For this purpose, each VN is characterized by a vector of $C \times \log_2(L)$ bits, where C is the number of context features, L is the number of levels (values) of a specific context, and $\log_2(L)$ are the bits used to describe all different levels of a context parameter.[4] For example, if $L = 4$ and we want to express how strong a characteristic is required, we may use the following intuitive levels: $-- \Rightarrow 00$, $- \Rightarrow 01$, $+ \Rightarrow 10$, or, $++ \Rightarrow 11$, where $++$ corresponds to a very demanding level of context required (e.g., high velocity or high security level which might correspond to larger keys for encryption procedures).
3. Each peer in the P2P control overlay represents a particular VN. The representative peer is randomly selected or chosen with the aim to balance the load between the physical nodes. Note that the same node may act as a VN representative for different VNs.

In Fig. 2, an example of a physical network and the P2P control overlay is described considering two context parameters (QoS, security), four levels for each parameter $(--,-,+,++)$, ten nodes in the WMN, and four context-aware VNs. In this simple example, the first two bits of each position of a VN key represent the QoS level of the VN, whereas the last two bits represent the security level of the VN. In this case, node A represents VN$_1$, C represents VN$_2$, G represents VN$_3$, and D represents VN$_4$. These peers are interconnected in the control overlay in consecutive order which allows fast lookup procedures. In case more than two context parameters have to be considered, the procedure is similar.

Scalability of this solution can be achieved by using two levels of P2P control overlays: a higher level overlay, where each peer represents a domain, and a lower level overlay with the control peers of each domain (the solution presented before focus on the context-embedding inside a domain). However, there are several issues that still need to be investigated, such as the location of a peer of a domain, and the size of a domain.

In our approach, context information does not have to be stored in all nodes of the network, because there is only one

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[4] Here, we assume equal number of levels for all context parameters; in the case of different numbers, the maximum number of levels should be taken.

peer responsible for each VN, which reduces the time to distribute the information per nodes. Moreover, overhead and latency for dealing with P2P solutions are reduced, because it is not necessary to always update the P2P control overlay after every change of the network. Finally, the P2P control overlay is organized in consecutive order of levels of context features, which alleviates the lookup procedure of the most suitable available VN for a user.

Two drawbacks of this approach are the potentially slow lookup procedure of finding the best VN for a user when there is a large number of VNs in the network, as well as, the behavior of the P2P control overlay in case a peer disconnects. However, each peer can establish some shortcuts with some specific peers, in order to accelerate the lookup procedure, and to provide the robustness, resilience, and fault-tolerance of the P2P control overlay (in analogy to Chord-based overlays [29]).

5.2 Management of virtual networks

According to user-centric information and mapping, the network aims to find and provide the best fitting personalized VN for each user. The following basic functions are introduced:

Selection of virtual networks: Based on the description of preferences and VN properties in terms of (meta-) information, matchmaking and selection is of the most suitable VN is performed. Hereby, a distance function is defined and used to determine this best fitting VN, e.g., evaluating the Euclidean distance of the preferences/context and the VN properties.

Creation of virtual networks: If there is a sufficiently large number of users with similar context preferences, a new VN is created fitting exactly these needs. The approach does not foresee the creation of VNs if only one or a few users demand a new VN.

Reconfiguration of virtual networks: If selection and creation is not feasible, we define a reconfiguration procedure of VNs. Reconfigurations are envisioned as light extensions to existing VNs with high impact to increase user satisfaction. A possible case for light-weight reconfiguration is a mobile device attached to a mesh router currently not part of the best fitting VN. A solution to this problem may need a minimal reconfiguration of a possible available VN, like the insertion of a virtual link between the mesh router (becoming a virtual mesh router of the VN) and a node of the VN. In order to react to changing user and network context, such as increase in load and sudden activities (e.g., groups of users suddenly all demanding a certain video stream), reconfiguration may also be very useful.

Concerning our proposed P2P control overlay, the management mechanism for the selection and (or) reconfiguration of the most suitable VN for a user is detailed next. If a user, with some context requirements, arrives at the network at some node (e.g., node A), we have to find and reconfigure the VN that best fits the requirements of the user, and four cases are considered:

1. If node A contains the VN that fits its requirements, the match is found.
2. If node A does not contain the VN that fits its requirements, it should communicate with its neighbors. If one physical or virtual neighbor of node A contains the VN, a new virtual link is added to this VN, in order to include node A.
3. If neither node A nor one of its virtual or physical neighbor belongs to the correct VN, a lookup procedure in the P2P control overlay is started to find a possible point of attachment on this VN. Note, if node A is a peer of another VN, the lookup procedure in the P2P overlay can start with this peer. If not, a possible peer of the P2P overlay has to be found where the lookup procedure can be started. At the end of the lookup procedure, if there is a point of attachment on the VN that fits the requirements of the user, a virtual link between A and this point of attachment is added.
4. If there is no VN in the network with these particular features of user context, another lookup procedure in the P2P control overlay is started to find the best available VN for the user. Note that another VN will only be created when there are several users with similar context-patterns in the network (number to be evaluated). The creation of a new VN requires the selection of a node representing this VN in the P2P overlay, and the insertion of this peer in the overlay maintaining the correct order.

At the end of every process, it is verified whether the communication target of the user is attached to a node that belongs to this VN. If not, we have to look at the address of the target of the communication and add a virtual link between the node where the target is attached and the closest node from of the chosen VN. In case context prediction is used, management activities may also be started proactively.

5.3 Context modeling and prediction use case: mobility context

Mobile users differ in their behavior with respect to velocity, direction changes, acceleration, pause times, etc. These characteristics can be used to assign users to different classes which make a difference for networking. From a networking scenario perspective where the mobile devices are clients only, mobility mainly influences connectivity of clients and handover characteristics (e.g., basic cellular inter-cell handover is known to suffer from border effects which can be due to disadvantageous locations; another

Table 1 Different cases addressed in the management of virtual networks

Processes	Values	Scen. 1	Scen. 2	Scen. 3	Scen. 4
Link-layer association	$T1 = 20$ msec	x	x	x	x
Transference of the user context	$T2 = 2$ msec	x	x	x	x
Processing time at the physical node	$T3 = 10$ msec	x	x	x	x
Processing time at the virtual node	$T3 \times V$	x	x	x	x
1st P2P lookup procedure	$(T2 + T3) \times V \times \log(V)$			x	x
2nd P2P lookup procedure	$(T2 + T3) \times V \times \log(V)$				x
Add of a virtual link	$2 \times (T2 + T3) \times N$		x	x	x

example is fast movement which causes high handover frequencies). For example, in case a user is traveling at an average speed of 130 km/h on a highway, the handover procedure has to be much faster than for a pedestrian walking at 4 km/h.

In order to describe mobility as context, the important parameters of mobility have to be specified. Among possible parameters, velocity and a description of the pathway (can be a direction or the history of subsequently visited locations) are here considered. These mobility characteristics allow to describe the movement appropriately—and to map it to the network relevant characteristics, that are, e.g., periods of connectivity and periods of non-connectivity (see also Sect. 6). In case future positions and velocities (or dwell times) are predictable based on history data, these periods can be estimated also for the (near) future.

By integrating mobility characteristics directly or indirectly after mapping them to timing characteristics, conclusions about the overall timing behavior of the multi-VNs can be derived. For example, in cases of extremely high velocity, it might make sense to attach not to every wireless mesh router but only to each second (in general, k_{th}) router, to avoid unnecessary attachment overhead. In other cases, VN configuration may be activated in proactive manner for highly mobile users. The best fitting VN for a user should include these additional mechanisms for mobility support.

6 Evaluation and discussion

In this section a discussion is presented, which aims at giving first insights about important performance characteristics of the proposed solution for context-aware characterization and management of VNs. To demonstrate the potential of proactive VN management, we add prediction (mobility prediction) to the approach.

6.1 Management of virtual networks

Here, we present an analytical evaluation of the *delays* introduced by the VN management process described in Sect. 5.2, where the VNs are characterized as presented in Sect. 5.1.

We assume that a user with a specific context requirement arrives at a WMN consisting of N physical nodes and V available VNs. We assume further that, for each type of context requirement, one VN is specified (C possible context requirements). This implies that one level for each context feature is considered ($L = 1$).

Scenarios and assumptions In this analytical study, we address the four different cases (possible scenarios) described in Sect. 5.2, in order to assign the user to the most appropriate VN. We assume that: (i) the target of the user communication belongs to the VN that fits its requirements; (ii) the number of VNs that exist in the network (V) is equal to the number of context features (C); (iii) the physical resources are uniformly distributed between the VNs; and (iv) every VN is supported in each of the N physical nodes.

Time considered For each scenario, the times of the different processes involved are summed up. The different processes of each scenario are described in Table 1 (times are average values). They are:

Link-layer association time: The link-layer association time is the time needed for an association between the user and the mesh node ($T1$, based on observations in the DAIDALOS project [37]).

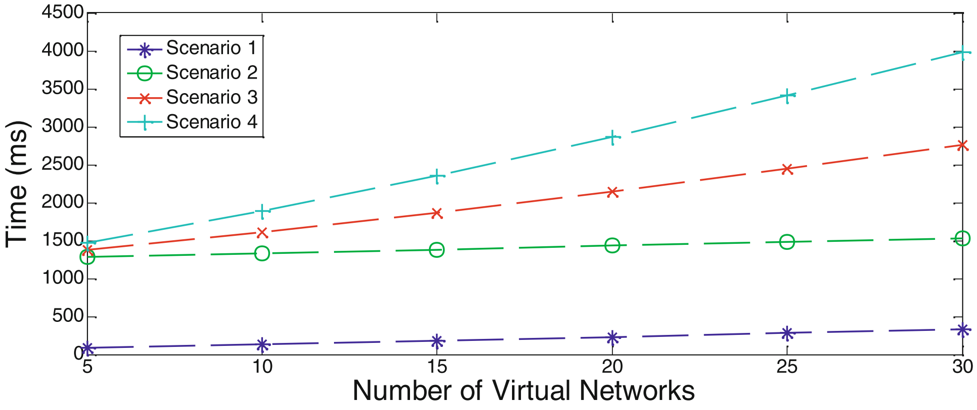
Time to transfer user context: This is the time for transferring the user context in a message over a wireless link to the mesh router ($T2$, as seen in [37]).

Processing time of the physical node: This is the time to verify, if the VN that fits the user requirements is available ($T3$, as seen in [37]).

Processing time of the virtual node: This is the time to update a virtual node of the VN. It is proportional to the number of VNs per node ($T3 \times V$); more VNs maintained on each physical node lead to less resources per VN (e.g., CPU), which results in an increased processing time of each virtual node.

Virtual link time: This is the time needed to connect the user node with the nearest point of attachment to the best available VN. This time is equal to find a path in the physical

Fig. 3 Times involved in each scenario



network between two physical nodes. It is proportional to the number of physical nodes in the network (N), and includes the time to transfer a message ($T2$) as well as the processing time of the physical nodes ($T3$). Moreover, it has to be multiplied by 2 because of the round-trip of these messages ($2 \times [T2 + T3] \times N$).

Lookup time: This time describes the time needed for lookup of the best VN in the P2P control overlay. This time is proportional to the complexity of the lookup procedure (as in the Chord-based overlay [29], $\log(V)$), and to the resources available in virtual links and nodes, which are proportional to the number of VNs ($(T2 + T3) \times V$). More VNs imply fewer resources for each virtual link and node, which leads to increased time to transfer ($T2$) per virtual link, as well as to increased processing time ($T3$) per virtual node.

Next, four different scenarios are investigated. In scenario 1 (see also Sect. 5.2), a user arrives at a node which belongs to the VN fitting the user requirements. Thus, only $T1$ and $T2$ have to be considered. In scenario 2, the best fitting VN is not available, but one of its physical or virtual neighbors can provide connection to this VN. Hence, a virtual link between the mesh router the user is attached to and a neighbor can be added. Scenario 3 further includes a lookup procedure in the P2P control overlay in order to find the best VN for the user. The last scenario (scenario 4) includes two P2P lookup procedures, because the exact match can not be found within the available VNs. These timings and scenarios are presented in Table 1.

In order to compare the times involved in each scenario, we consider that there are 50 mesh nodes in the physical network and an increasing number of VNs (5, 10, 15, 20, 25, and 30). The results obtained through this analytical study are depicted in Fig. 3.

Discussion of the results We can conclude that, if there is a large number of VNs in the physical network, there will be a larger processing time per virtual node and virtual link, which affects the total time needed for each scenario. With more physical nodes in the network, more time is required to find a path in the network in order to establish virtual links, which implies more time to establish the connection between the user and the reconfigured VN fitting the user context requirements. Scenario 1 is independent of the number of nodes in the network; it only depends on the number of virtual nodes per physical node. The difference between scenarios 2 and 3 (more than 1 sec for 30 VNs) is due to the lookup procedure in the P2P control overlay; note that scenario 4 includes two of these procedures.

While the first scenario contains time for reconfiguration in the order of 300 msec for 30 VNs, in the fourth scenario it can reach 4 sec. We conclude that careful configuration of the network in terms of required number of VNs and selection of nodes supporting specific VNs, is required to avoid long delays for reconfigurations. In order to reduce these delays, proactive mechanisms based on prediction approaches can be advantageous.

6.2 Mobility-awareness use case

For demonstrating the usefulness of using mobility context and mobility prediction, we consider a particular topological model for mesh routers and user mobility.

Assumptions Mesh routers are placed in a regular grid and operate at the maximum transmission power of 20 dBm in the 2.4 GHz band. The distance between the mesh points is assumed to be $d = 100$ m [38]. With respect to movement, we assume pedestrians in a city and vehicles on a city highway. Pedestrians are assumed to travel with a speed of $v = 1.34$ m/sec [39] and vehicles with $v = 33.33$ m/sec (120 km/h), cf. [40, 41]. For simplicity reasons, we assume that mobile nodes travel straight using the shortest distance to the next mesh router, meaning that each mobile node attached to one mesh router reaches the next mesh router in distance d. In other words, pedestrians change mesh routers

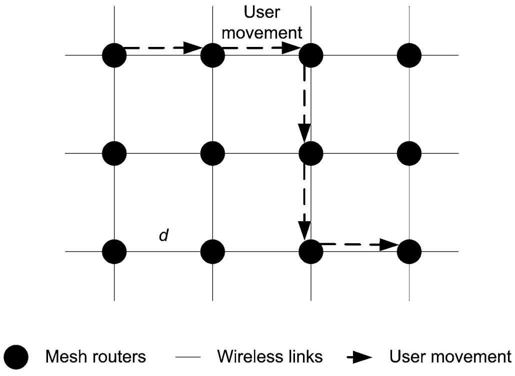


Fig. 4 Mobility-awareness use case: assumed topology of the mesh network and user movement

every 74 seconds and vehicles every 3 seconds. Figure 4 visualizes the assumed simple topology.[5]

Time considered Physical movement of mobile devices requires considering a number of time averages. Figure 5 visualizes these time averages, they are:

Connection and disconnection time: T_C and T_{NC} describe, respectively, the time a node is connected to a mesh network via a mesh router or not connected.

VN management time: T_{VN} is the sum of all times necessary to support the VN-based connection management. In the general case, some parts of the VN management are designed to be done proactively (respective avg. time T_{VNpro}) before the mobile terminal signs up to a mesh router, and some activities can only be processed in reactive manner (respective avg. time T_{VNre}).

Service time: To evaluate the potential of prediction, we introduce T_S, which is the time remaining for service execution.

Prediction time: For prediction, we introduce T_P, which is the time necessary to do the prediction and to transfer mobility information to the mesh network. These activities are assumed to take place once per attachment. T_P, as considered here, reflects only the time necessary to do a prediction given a current history state; the time for generating the current history state, for example, logging of position data at a specific frequency, like 1/sec for off-the-shelf GPS hardware, is done in parallel. The predictor simply takes the last k history position states to estimate the next position(s).

As our model should give an insight into timing issues and not into the accuracy of a particular predictor, we assume a perfect predictor capable of estimating the next position, which, of course, does not hold for real-world situations. It is possible to start prediction some mesh attachments ahead, but it is most likely that prediction errors sum up quickly leading to inaccurate predictions. Hence, we assume that prediction is done only one attachment ahead. T_P is the sum of the time necessary to do prediction, the time necessary to transfer next position information to the mesh (assumed to be similar to $T_2 = 2$ msec in Table 1), and the time necessary to lookup the mesh router closest to the predicted next position within the network to finalize prediction. As the time for prediction and lookup heavily depends on the predictor type (e.g., on the data structure used to store mobility regularities, number of position entries), the time assumed here is just an example for the cases that have been studied in a previous project under similar topological and distance assumptions of a wireless data grid [42]. Commonly used predictors have been investigated after training based on the GPS data of a taxi fleet in Vienna collected over one month. For a k-order Markov predictor, we investigated the prediction time of five taxis on a standard PC leading to prediction times varying between 2 msec and 80 msec (for the LeZi Update predictor, the prediction time always remained below 4 msec). As a consequence of these experiences, we set $T_P = 10$ msec for our use case. (See also related assumptions for online computation of predictions in the range of 10 to 50 msec [43].)

First quantitative insights Given these model assumptions, we can now calculate the remaining service time T_S without prediction, which is calculated as:

$$T_S = \begin{cases} T_C - T_{VN}, & \text{if } T_C > T_{VN}, \\ 0, & \text{else.} \end{cases}$$

For prediction, we make a distinction between parts of the VN management which can be done proactively and parts which cannot, hence, $T_{VN} = T_{VNpro} + T_{VNre}$. Depending on the relation of the VN management times to the connection time, several cases for service time calculation can be distinguished for one attachment period. These cases are (assuming $T_P \leq T_C$): (i) overhead and prediction do not leave any remaining time for service execution (note that we consider $2 \times T_C$ and T_{NC} as the time in principle available for proactive and reactive overhead and service execution); (ii) the proactive part of the VN management can be done before attaching to the next mesh router, and the reactive part can be started and finished during the following connection time; and (iii) the proactive part cannot be finished before attachment, hence, some of the proactive activities are done after attachment. For perfect prediction, the three cases mentioned lead to alternative service time calcu-

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[5] Note that we refer here to the physical resources as wireless mesh connection points.

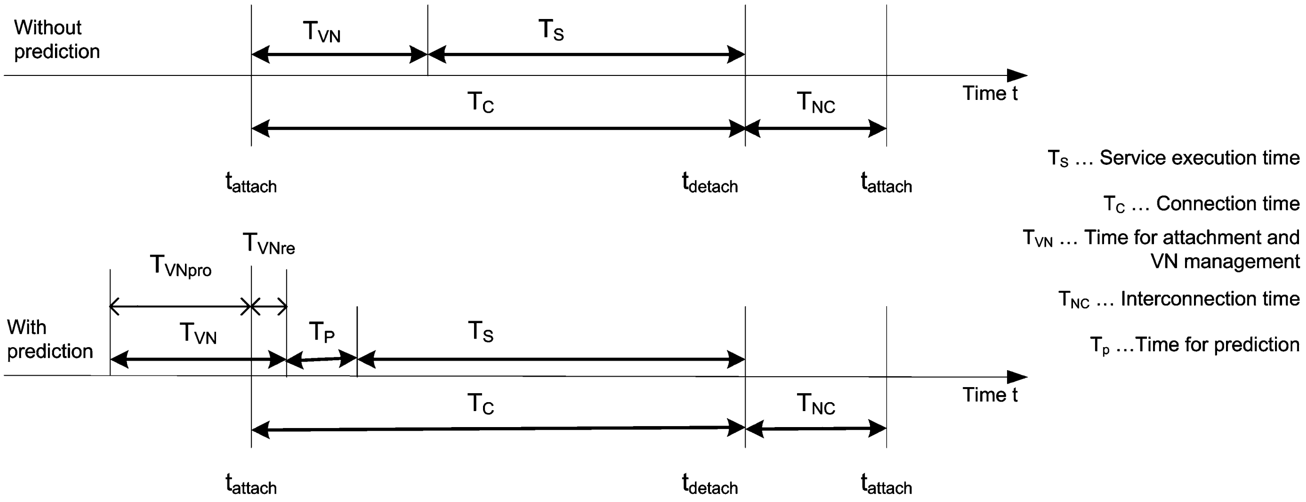

Fig. 5 Considered times with and without prediction

Table 2 Service time T_S (in seconds) with and without prediction for pedestrians and vehicles, number of VNs fixed to 30 cf. Fig. 1, $T_P = 0.01$ s, and varying T_{VN} for Scenarios 1 to 4

Cases	T_C	Scenario 1 $T_{VN} = 0.4$ s	Scenario 2 $T_{VN} = 1.5$ s	Scenario 3 $T_{VN} = 2.75$ s	Scenario 4 $T_{VN} = 4$ s
Pedestrian w/o prediction	74 s	73.6 s	72.5 s	71.25 s	70 s
Pedestrian with prediction	74 s	73.99 s	73.99 s	73.99 s	73.99 s
Vehicle w/o prediction	3 s	2.6 s	1.5 s	0.25 s	0 s
Vehicle with prediction	3 s	2.99 s	2.99 s	2.99 s	1.98 s

lations:

$$T_S = \begin{cases} 0, & \text{if } 2T_C + T_{NC} < T_{VN} + 2T_P, \\ T_C - T_{VNre} - T_P, & \text{if } T_C + T_{NC} \geq T_{VNpro} + T_P \\ & \text{and } T_C \geq T_{VNre} + T_P, \\ 2T_C + T_{NC} \\ \quad - T_{VN} - 2T_P, & \text{else.} \end{cases}$$

Hence, based on the times and scenarios defined previously for the pedestrian and vehicle use case, we can calculate the benefits when using prediction in terms of service time. To demonstrate the potential of prediction, we set $T_{VNre} = 0$ msec, meaning that all VN management activities can be done proactively. Moreover, we assume full mesh coverage, hence $T_{NC} = 0$ msec. Table 2 summarizes the calculated results.

The benefit of prediction depends on the relation of T_{VN} and T_P, which is in our scenarios always in favor of the prediction. In Scenario 4, without prediction, vehicles attach/detach too fast to be able to finish VN management ($T_{VN} = 4$ s) and prediction is crucial to allow VN management to finish before the vehicle detaches again. With prediction, VN management can start during the previous attachment period right after prediction (time required for prediction is $T_P = 0.01$ s per attachment period). Hence, only 1.01 s of the current attachment time is required to finish VN management, another 0.01 s for next prediction, and the mobile device may use the VN in the remaining $T_S = 1.98$ s (while without prediction, not even VN management could have been finished).

Discussion of the results The proposed architecture undoubtedly introduces overhead and complexity in the control and management of the network, through the mapping and integration of context in the network, multiple VN support, and all the processes required for the reconfiguration of the network when changes on users and context are in place. The overhead and delays associated with the control and management of the architecture are higher than in traditional networks, and the times required to start a communication will also be higher. However, this is the cost to pay for the support of context-aware and user-provided networks.

We have simplified several complex timing considerations to be able to give a first insight about the possibilities of prediction. In particular, *perfect prediction* was assumed and the possibilities of inaccuracies and wrong predictions were neglected. More realistic assumptions will have to be investigated in future work. Moreover, it was assumed that right at the point of attachment, the prediction is done for the next attachment only. In principle, this restriction can be released, but it possibly leads to more inaccurate predictions in a real prediction setting. We plan to devise new mechanisms that will improve all these processes to enable the simple support of context-aware user-provided networks in the future.

7 Conclusion

In this paper, the importance of introducing context has been argued to provide highly adaptive WMNs. With the demand of such flexible WMNs, a novel architecture consisting of multiple virtual networks has been proposed and selected related work, which demonstrates the importance of providing solutions to integrate context in WMNs, has been surveyed.

The contributions of the approach are twofold: first, we have followed the concept of multiple virtual networks and proposed an architecture to map and control them in a distributed manner in the physical network; second, we have incorporated a prediction component for device mobility to improve the proposed architecture. The results showed that the complexity of the reconfiguration processes can be significant, and that prediction-based approaches may be crucial to improve the overall performance.

Although an architecture has been specified, there are numerous issues that need to be addressed in the future. The development of more advanced performance evaluation models including multi-homed devices and multi-path connections, the cross-connection of multiple context-based VNs, the resource management provided through energy-efficiency purposes, and a complete model of the proposed architecture and mechanisms, are only some of the issues to be researched in order to provide a complete context-aware user-driven network architecture.

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