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Symbiotic Networks: Towards a New Level of Cooperation Between Wireless Networks

Eli De Poorter · Benoît Latré · Ingrid Moerman · Piet Demeester

Abstract In the future, many wireless networks, serving diverse applications, will co-exist in the same environment. Today, wireless networks are mostly optimized in a rather opportunistic and/or selfish way: optimizations methods only use a local view of the network and environment, as they try to achieve the best performance within its own network. The optimizations are very often limited to a single layer and cooperation between networks is only happening through the use of gateways. In this paper, we suggest an alternative paradigm for supporting cooperation between otherwise independent networks, called 'symbiotic networking'. This new paradigm can take many forms, such as sharing of network resources, sharing of nodes for communal routing purposes and sharing of (networking) services. Instead of optimizing network parameters within the individual networks, symbiotic networking solutions operate across network boundaries. Parameters are optimized between the networks and communal protocols are developed, leading to a more global optimization of the scarce network resources. In this paper, we describe several scenarios which can profit from symbiotic networking and illustrate a strategy for supporting networking protocols which can operate across network boundaries. Ultimately, through the disappearance of network boundaries and the introduction of cross-layer/cross-node/cross-network cooperation, symbiotic networks takes the notion of cooperation to a new level, paving the way for a true network symbiosis.

Keywords Symbiotic networks · Wireless networks · Cooperation

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1 Introduction

Future environments will undoubtedly be equipped with various wireless networks serving many applications: WiFi access points for internet sharing, wireless sensor networks (WSNs) for home and office automation, cordless phones, etc. From these day-to-day examples, it is clear that many wireless networks will co-exist in the same environment.

Currently, wireless networks try to achieve the best performance within their own network and hereby neglect the impact on other co-located wireless networks: they are optimized in a rather selfish way and optimization methods only use a local view of the network and environment. The few existing solutions for co-existence between wireless technologies are often limited to a single layer withing a single network domain. As such, current solutions do not result in efficient communication from a global point of view. By restricting cross-layer optimizations within the network boundaries, many cross-network optimization opportunities are not used, leading to a sub-optimal global situation.

The *'Symbiotic Networking'* paradigm proposed in this paper aims to fill this gap, cooperating across all layers and across network boundaries. Much more efficient solutions in terms of spectrum, energy consumption and QoS guarantees can be achieved when these different networks are aware of each other and act accordingly, i.e. when they truly cooperate. This way, a global optimum can be achieved across different networks occupying a common shared medium.

Using symbiotic networks, advanced cooperation is possible between otherwise independent networks. This cooperation can take many forms:

- The sharing of information, such as environment information or spectrum information;
- The sharing of infrastructure such as processing capacity or the sharing of each other nodes for routing purposes;
- The sharing of (networking) services, can be offered to each other, such as positioning, synchronization, address translation, QoS functions, code updates, security provisions or internet connectivity.

The use of symbiotic networking not only results in better use of the available resources, but also enables several new applications. Examples of these use cases can be found in Sect. 3. The rest of the paper is organized as follows: in Sect. 2 an overview is given of current work which has tackled cooperation between networks. Next, in Sect. 3 a proper definition of symbiotic networks is given and illustrated through several use cases. The next section describes a strategy for designing protocols which support symbiotic networking. In Sect. 5, a possible framework for supporting symbiotic networks is briefly discussed and in Sect. 6 several additional challenges are given for supporting symbiotic networking. Finally, a summary and conclusions are given in Sect. 7.

2 Broadening Current Research

2.1 Evolution from Existing Networking Paradigms to Symbiotic Networking

In the last few years, the first step towards closer collaboration between different wireless networks has been taken. In general, five types of collaboration can be distinguished (see Fig. 1): cognitive radio, cognitive networking, opportunistic or delay-tolerant networking, cooperative networking and inter-networking.

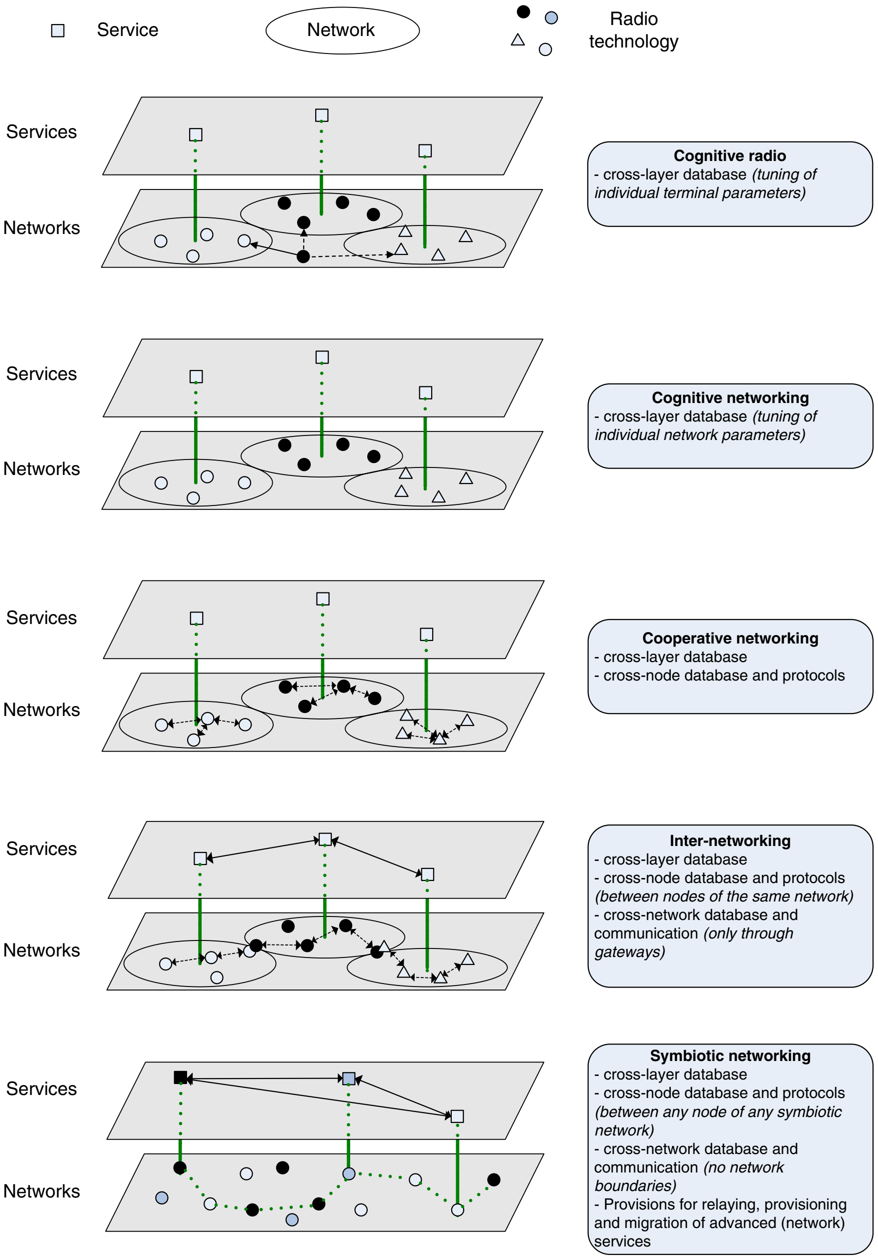

Fig. 1 Types of collaborations

Cognitive radio can be seen as a paradigm for wireless communication, in which a wireless node autonomously reconfigures its transmission parameters based on the environment in which it operates [23]. Two main user scenarios exist: (1) reuse of unused licensed spectrum without interfering with licensed users; (2) exploit multiple access technologies in view of optimal connectivity (also known as ABC or Always Best Connected paradigm).

Cognitive networking is a paradigm where a wireless network intelligently adapts its network parameters based on the active monitoring of the environment (application, terminal, network, radio). This allows the node to communicate efficiently without interfering with licensed users [3, 17, 31]. This alteration of parameters is based on the active monitoring of several factors in the external and internal radio environment, such as radio frequency spectrum, user behavior and network state. The knowledge data base and the decision engine are the central components of the cognitive architecture. Basically, it performs a mapping of changes in the situation (of an application, terminal, network,. . .) towards a change of the configuration (of the application, terminal, network,. . .) [5, 9]. The efficiency of decision-making will greatly depend on the method and metrics chosen for a certain optimization.

Cooperative networking is a concept where nodes in a network share resources to create collaboration through distributed transmission, relaying and/or processing (e.g. coding). Current research on cooperative networking is mainly restricted to a single network and cooperation within a single layer [18, 24]. The concept has been introduced in many publications in many different contexts. Examples are numerous, such as [20], in which an efficient MAC protocol is developed for wireless sensor networks, and [12] where communication reliability is increased by using the broadcast mechanism with cooperating nodes.

Opportunistic networking or delay-tolerant networking can occur when a part of the infrastructure is not fixed but exists of mobile devices or in an environment in which devices often appear and disappear. Data exchanges can take place using the connection opportunities that arise due to impromptu encounters with other devices: nodes can forward data from the source to the destination by using connections with temporary neighbors [26]. Opportunistic Networks enable users communication in disconnected environments, in which islands of connected devices appear, disappear, and reconfigure dynamically. No assumption is made on the existence of a complete path between the end points. Opportunistic Networks are very suitable to support the pervasive networking scenario, in which a huge number of devices carried by users and embedded in the environment communicate wireless without requiring any pre-existing infrastructure [19]. A special form of opportunistic networking is delay tolerant networking [33] where a message is forwarded whenever a connection is available.

Inter-networking enables communication between independent networks through the use of translation gateways, also called anchor points [2]. This type of collaboration is often used to extend the ABC paradigm in case no direct Internet connection is available and connectivity is provided through relaying over multiple networks.

In Table 1 the characteristics of these networking types are compared with the wanted features of symbiotic networks.

2.2 Relation with Existing Projects

The ‘Ambient Network’ project [2] has many of the same goals as our proposed symbiotic networks. They aim at specifying and deploying a control plane to be integrated with current networking and communication architectures. Therefore, they developed a common naming framework and several interfaces for enabling end-to-end communication between heterogeneous networks. Further research efforts include advanced hand-over schemes, mobility support and several forms cooperative and cognitive networking. They do not aim for a solution in which networks truly coordinate over each networking layer. Though they ‘merge’ different networks, this merging uses traditional gateway nodes and does not include the use of communal networking protocols or the sharing of resources such as nodes for routing purposes.

Table 1 Some characteristics of different networking paradigms

	Opportunistic networking	Cognitive networking	Cooperative networking	Inter-networking	Symbiotic networking
Intra-node optimization	No	Sometimes (cross-layering)	Sometimes (cross-layering)	No	Yes (cross-layering)
Optimization in the same network (intra-network coordination)	No	Yes (mostly physical layer)	Yes (in a single layer)	No	Yes (in all layers)
Optimizations between different networks (Inter-network coordination)	Limited (between two islands of the same technology)	Limited (interference avoidance on physical layer)	No	Yes (communication through gateways)	Yes (even without gateways)
Support for dynamic connections	Yes	No	No	Yes (only through gateways)	Yes (through any compatible node)
Exchanges of traditional services (application level services)	No	No	No	Yes	Yes
Exchanges of networking services (services for supporting lower level cooperation)	No	No	Yes	No	Yes
Often used techniques		Multiple radio interfaces, software defined radio, spectral efficiency	Cross-layering	Gateway translation, information exchanges	Combination of all these techniques

The ORACLE project [25] addresses “Opportunistic Radio Communications in Unlicensed Environments”. The project is elaborating scenarios and use cases for opportunistic spectrum use in the 2.4 GHz ISM band and in the licensed UMTS band. It will investigate reconfigurable terminal architectures, spectrum sensing methods, cognitive methods based on context-awareness and usage policies as well as simulation models for opportunistic spectrum users. The project also expects to address collaborative sensing and decision making for networks of agile radios. The project does not address cross-network solutions but can result in concepts useful for enabling symbiotic networks.

The End-to-End Reconfigurability (E2R) project [8] researches ‘reconfigurable devices system functions to offer an extensive set of operational choices to the users, application and service providers, operators, and regulators in the context of heterogeneous systems’. They focus mainly on handover systems, bridges and software-defined radios. Other related projects are GOLLUM [11] (developing an operating system independent link-layer API to support heterogeneous systems), CORVUS (focusing on opportunistic spectrum use and associated network architectures), MAGNET [21] (secure Personal Networks in multi-network, multi-device, and multi-user environment) and 4G [1] (about network convergence beyond the current 3G technologies). All these projects are useful enablers for symbiotic networking, but they do not take the step of truly abandoning the network boundaries.

Finally, several task groups exist which are actively developing standards. IEEE 802.21 [15] is developing standards to enable handover and interoperability between heterogeneous network types including both 802 and non-802 networks. IEEE 802.22 [16] is developing a standard for a cognitive radio-based interfaces for use by license-exempt devices on a non-interfering basis in spectrum that is allocated to the TV Broadcast Service.

2.3 Symbiotic Networking: Terminology

The term ‘Symbiotic Networks’ is not new. It was first used in [10], where the symbiotic network is envisaged as an extension of ad hoc networks where devices make use of each others resources in order to extend their own capability. The main use is to extend the reach of a WLAN access point. However, the notion of cooperation in this paper is rather limited, and we think the term symbiotic network is more appropriate for networks in which cooperation is more explicit and advanced. Furthermore, ‘Overlay Symbiotic Networks’ for wired networks are discussed in [32]. Finally, [4] handles about Symbiotic Highway Sensor Networks and approaches the most our definition of symbiotic networking as the data of the sensor network along the highway is sent to the internet via an intermediate mobile ad hoc network consisting of vehicles. However, the cooperation is still very limited and static as a pre-defined gateway is used between the sensor network and the ad hoc network and both networks act separately. Neither the interaction between both networks or optimizing the globally network optimum are considered.

3 Definition and Use Cases

The current research shows that there is a trend towards more advanced cooperation between wireless networks, but we wish to go a few steps further. Using symbiotic networking, the sense of cooperation is broadened, is not focused on only a single application and is compromised of multi-layer cooperation. We start with giving a proper definition of symbiotic networks:

> *Symbiotic networks* are (wireless) network that cooperate across all layers and across network boundaries through advanced sharing of information, infrastructure and (networking) services. The individual networks can fully operate on their own, independently run their own set of services and functionalities but new functionality is introduced in the network and more energy-efficiency or increased reliability can be obtained.

In order to get a better grasp on what symbiotic networks actually are and how they can proof to be useful in the future, a few small examples are given below.

3.1 Home and Office Environment

In the near future, consumer environments will become more and more equipped with WSNs. Although a single wireless sensor network may integrate diverse monitoring & control applications, there is no doubt that multiple WSNs and other wireless networks will coexist in the same area. Many wireless technologies use the same unlicensed spectral band, like WiFi, Bluetooth, ZigBee, DECT. Today, such networks can only coexist by manually tuning radio frequencies. However, with the Symbiotic Networking paradigm, two (or more) totally independent sensor networks could decide to cooperate and use each other's nodes for more optimized and more energy-efficient routing. Nodes can even decide to exchange code in view of having more advanced functionality such as e.g. QoS support functions. Furthermore, in most cases, one or more WiFi access points will be available. The WSN can provide interference information to nearby WiFi nodes. Doing so, the WiFi network is given a global view on the environment and can take appropriate actions to reduce interference (e.g. through a negotiation process between WiFi network and co-located WSNs). The WiFi nodes in their turn can provide relay services and localization information to the WSN and hence reduce the load in bandwidth- and energy constrained WSNs. Current solutions do not provide generic mechanisms to detect co-located networks which are operating at different frequencies or different radio modes, to adapt transmission parameters and routing strategies in view of merging networks, to define and agree on incentives for accounting the benefits of the cross-network cooperation, and to exchange code for enhanced functionalities. Furthermore, no strategies for a global interference reduction (today interference avoidance is based on local decisions) exist.

3.2 Body Area Network and its Environment

In a Wireless Body Area Networks (WBAN), sensors are placed on the human body where they monitor physiological parameters like heartbeat, body temperature, motion, etc. The benefit of WBANs can be extended when they can interact with other networks. For example, when a person is wandering in a city, the WBAN can receive information about interesting places or the history of the building, or the WBAN can be informed by another network when the air pollution in a certain region is too high. Or when a driver is in his truck, his WBAN and the truck network can 'merge', becoming truly one network. The vehicle can monitor the status of the driver, automatically alerting the driver and notifying surrounding vehicles, should the driver fall asleep. The WBAN can request whether products are being transported to which the driver is allergic. Furthermore, the truck network can detect the WBAN of bicycle drivers nearby, thereby reducing the chance of fatal accidents. If the WBAN detects that its wearer has a heart attack, the network could automatically connect with a nearby network (e.g. an eCall network or the cell phone worn by the person next to him) and use that network to call an ambulance or alert a doctor. In the ambulance, the WBAN and the network of the ambulance merge instantly. The life signs of the patient are shown on screens in the

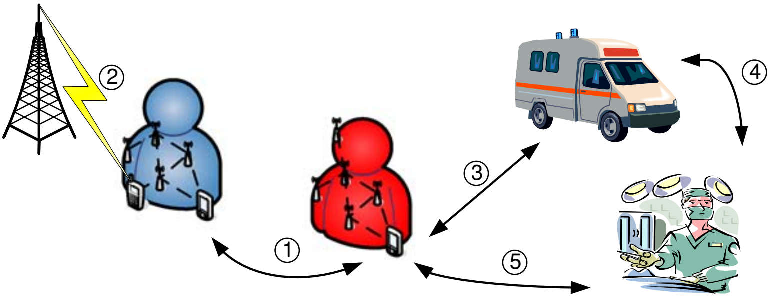

Fig. 2 Possible interactions with a Wireless Body Area Network in an emergency situation. (1) the WBAN connects to a neighboring network and (2) uses the cell phone. When in the ambulance, the WBAN sends information to the ambulance (3) and hospital (4). At the hospital, the doctors can use this information (5)

ambulance and the uplink of the ambulance is used to send the patient data to the hospital. When the patient arrives in the emergency room, the WBAN cooperates with the hospital infrastructure and monitoring information is automatically displayed at large screens in the emergency room and can hence be easily accessed by the medical staff. This is illustrated in Fig. 2.

3.3 Emergency Services

In a crisis scenario where emergency services respond to a call, it is very important to have dependable access to the ICT facilities of the involved forces such as the fire brigade, police or medical services. When using symbiotic networks, the emergency services have no need to deploy new devices for monitoring and communication: existing network infrastructure, such as home networks, can be used (see Fig. 3). When an intervention is needed in a house, the network of the arriving fire force will automatically connect to the home network of the house or surrounding buildings. In case of a fire, temperature readings and video images can

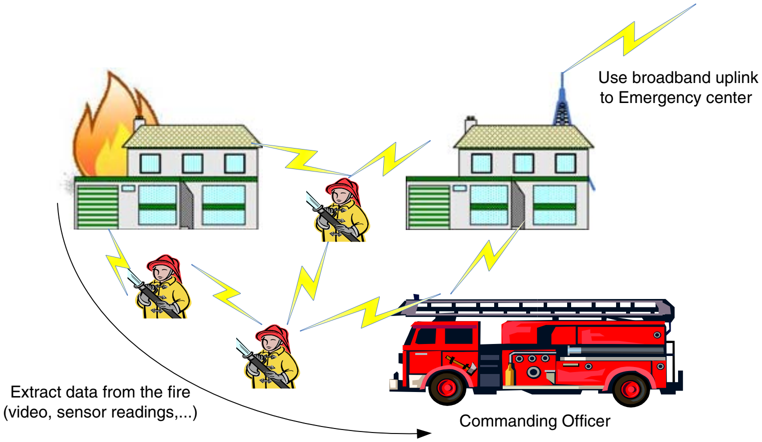

Fig. 3 When emergency services arrive at the scene, a symbiotic network is formed for dependable access to the ICT services and to extract critical data from the fire

be sent to the firemen for inspection. Using this information, the nature and the exact place of the fire can be determined and the firemen will know if anyone is still in the building. Two firemen walking in the home can use the existing network, wired or wireless, for their communication purposes. The home networks of the surrounding houses can provide a broadband uplink to the internet and to the emergency center for video streaming. These paradigms are also of interest for the military applications.

3.4 Vehicular Networks

In the near future wireless technologies will be an integrated part of vehicles. These intelligent vehicles can automatically interact with other intelligent vehicles, e.g. propagating warnings about lane changes, accidents, inter-vehicle passenger communication,… Vehicles can also communicate with intelligent roads for electronic toll collection, real time information about traffic signals, work zones or hazard warning distribution. The road network can receive information from priority vehicles to allow for a smooth passing by adjusting the traffic lights. This requires a combination of very heterogeneous technologies and fast network detection. Today very specific architectures are developed for vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I). These architectures are optimized in view of vehicular applications, hereby relying on dedicated vehicular network infrastructure, and hence do not take into account other co-located networks. By introducing symbiotic networks solutions, the V2V and V2I communication will be more efficient and the reach of vehicular applications can be extended, as other co-located networks can assist in propagating vehicular information.

Therefore, the symbiotic network should support self-organization and automatically reorganize itself to maintain and optimize the connectivity required to support the applications in dynamic network environments. New networks or new network devices should be automatically and quickly detected and incorporated in the symbiotic network. The new functionality of these devices should be made available to the rest of the network. These small examples show that new and advanced applications may be developed when these networks coordinate in more advanced ways.

4 Cross-Network Cooperation Strategy

Current networks do not have the cross-node protocols that are needed to support a symbiotic network. As such, there will be a strong need for a protocol suite to support symbiotic networking. To this end, in this section the DiNS strategy is being introduced, which can be used to organize newly developed protocols. The DiNS strategy consists of three consecutive phases:

1. *Di*stributed Network Discovery: detecting and identifying co-located networks in a distributed way.
2. *N*etwork Binding: the exchange and negotiation of network parameters and the development of common multi-layer networking protocols.
3. *S*ervice Convergence: entails mutual service discovery and provisioning protocols, as well as the provision of communicating incentives for symbiotic networks.

Using the DiNS strategy, we will address several possible implementations for protocols in each phase.

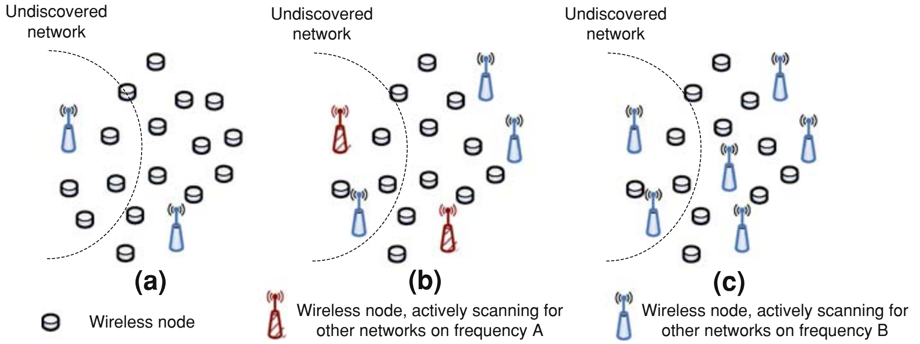

Fig. 4 Distributed Network Discovery. (**a**) A subset of the wireless nodes is used for detecting other networks. (**b**) Other wireless nodes can be used to scan in parallel on different frequencies to ensure the timely detection of symbiotic networks. (**c**) Adding more detection nodes increase the probability of successful detection

4.1 Phase 1: Distributed Network Discovery

The first step in forming a symbiotic network is the detection of other nearby networks capable of symbiotic networking. This can be done for example by using distributed algorithms. These dynamically select a dedicated set of nodes that scan a specific frequency (see Fig. 4). Optimizations are possible by taking into account the position of the available scanning nodes and the available radio interfaces. Using this information, the optimum number of participating nodes should be determined, as using too many nodes may be energy inefficient in dense networks. In order to speed up network detection, several nodes may scan in parallel on different frequencies.

To cope with the heterogeneous wireless environment, nodes with several wireless interfaces can be introduced. A more advanced solution is the use of software-defined radios (SDRs) [17, 28] which can change their transmission or receive parameters.

It is advantageous to define a specific broadcast protocol which can be used for detecting symbiotic-capable networks. This will also facilitate the initial communication. Several approaches can be taken. It is possible to use a dedicated broadcast protocol, which is supported by a set of nodes, but it is also possible to adapt or develop an extension to existing MAC protocols. The latter approach has the advantage that existing networks can still use standard MAC protocols for their regular communication. A simple example of an extension of current protocols might be to introduce beacons, sent at regular intervals on a predetermined frequency with predetermined radio parameters, which can be overheard by other networks in order to discover new networks.

Further protocols for the dissemination of information about the discovered symbiotic networks need to be developed. This information depends on the level of cooperation. For example, in order to negotiate the reuse of the spectrum, the spectrum used and the quality of this detection is propagated. For a better scheduling, usage patterns and time slot division are needed.

4.2 Phase 2: Network Binding

When other symbiotic-capable networks are detected, communication with the new network should be enabled so that a 'merge' of symbiotic networks can be established. Network

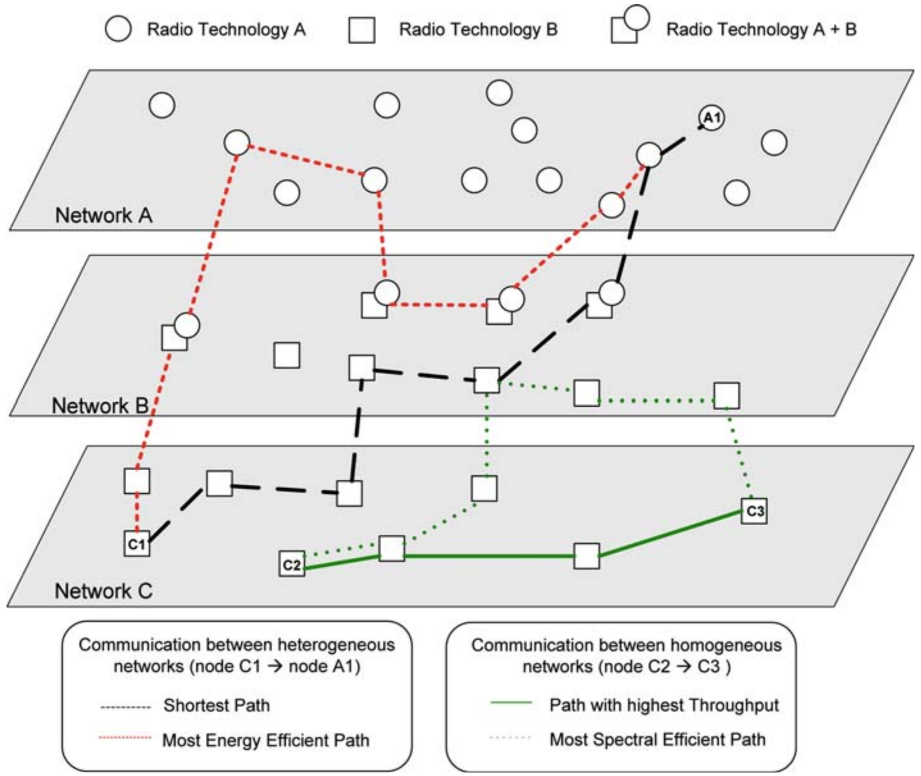

Fig. 5 Phase 2—network binding: routing example. Two scenarios are considered. (1) Node C1 has a connection with node A1. This connection uses the multi-radio nodes of network B. The path can be optimized in number of hops or in energy efficiency (2) Node C2 communicates with node C3. The most energy efficient path uses the nodes of network B

binding or negotiation is a potentially complex process, that entails the matching of network characteristics (i.e. frequency, modulation scheme, hopping sequence, . . .) and methods for agreeing on MAC, routing protocols, common synchronization protocols and localization protocols.

Advanced protocols will be developed that use SDRs to coordinate distributed interference avoidance algorithms and to match transmission parameters between symbiotic networks. Like in the network discovery process, the heterogeneous environment requires the use of multi-interface gateways or SDRs, enabling true ’node sharing’ between different networks.

Furthermore, adaptive routing protocols should be designed. It is important to note that traditional *translation gateways*—simply translating packets from one technology to another—are not sufficient to accomplish symbiotic networking with true node sharing. Instead, *negotiation gateways* need to be developed. These gateway nodes are responsible for bridging differences in wireless technologies between networks. Using these translation gateways, symbiotic networks will dynamically detect nodes from overlapping networks (cooperative sensing) and incorporate detected nodes (also non-gateway nodes) in their protocols. The networks can be considered truly ‘merged’, since overlapping networks do not just interact using gateways, but use each other’s nodes for common communication purposes, hereby using globally optimized networking protocols (see Fig. 5).

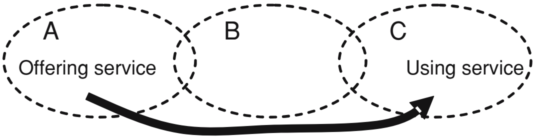

Fig. 6 Relaying of services between different networks in a symbiotic network

Negotiation gateways are thus able to interpret, process and control signals and parameters from different networks or network technologies, and allow the interworking with legacy systems. Currently, no protocol exist which supports this advanced form of adaptive cooperation and protocol matching.

Once network binding is completed, the networks can be considered '*merged*': they behave as if their nodes are all part of the same network. Of course, the process of merging networks cannot continue indefinitely: newly joining networks are only of interest to the original network as long as they are co-located or offer interesting services. As such, the knowledge about participating networks should be limited to the nodes which are effectively overlapping with the original network.

4.3 Phase 3: Service Convergence

Finally, the merged networks need to learn each others functionalities and services and they need to know how they can optimally make use of each others functionalities. Examples of possible services are the exchange of positioning or synchronization information, available processing power or provisions for address translation and security and authentication information. For example, if the nodes of a network are equipped with a GPS-receiver, their location information can be used by the nodes of the other networks. Further, mobility effects and network dynamics on the service discovery needs to be considered.

Finally, a mechanism should be developed for indicating which networks can make use of the offered services. This mechanism should include support for relaying services, thereby offering services from other networks to their own neighbors, Fig. 6. As an example, network address translation may be made available to all networks, with a maximum of two networks in between. The sharing of location information (giving high level information about the environment, such as 'rural', 'city', etc.) on the other hand may be limited by the numbers of nodes or a physical barrier rather than the number of networks.

5 Modular Framework

Many different protocols need to be developed, either as an add-on to existing networking software or as an all-in-one solution in which all protocols can be integrated. As such, there will be a strong need for a protocol suite to support symbiotic networking. An optimal integration can be obtained by choosing for an all-in-one solutions such as a framework. This framework should be easily reconfigurable and support cross-layer exchanges, code exchanges and code updates, as the protocols need to be adapted on-the-fly to allow the networks to talk to each other.

Current solutions for integrating protocols are lacking in several ways. They are mostly based on strictly layered structures [30]. This way, a specific layer needs no information about the inner workings of lower or higher layers. The advantage is that the functionalities at different layers can be altered without any impact on the other layers. Thus development and integration cost is less and testing is easy. However, this strict separation is not suitable

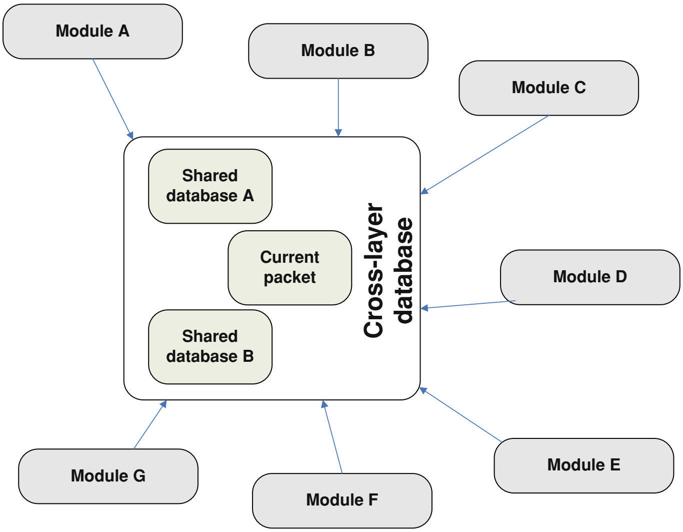

Fig. 7 Using a modular approach, functionality is divided in modules which interact through a cross-layer data repository

for wireless networks [22, 29]. The use of cross-layer approaches have several advantages: optimization is possible at several layers at once, a global optimization can be achieved and conflicts in optimizations at different layers can be avoided. In [6], Overall Sensor Network Architecture (SNA) is proposed which forms a narrow waist that connects the network layer and link layer. The cross layer approach forms a first step towards a more uniform architecture for wireless networks. However, SNA does not support heterogeneity (whereas symbiotic networks will consist of very heterogeneous devices) or easy code exchanges.

For symbiotic networks, we propose a modular architecture for wireless nodes where the functionalities are modules that can be plugged into the architecture [7]. In this modular approach, functionality is divided in modules which can interact with each other (see Fig. 7).

This modular approach has several advantages:

- Duplication of functionality can be avoided. Classic examples of duplicate functionalities are error correction and retransmission which are currently implemented in several layers of the protocol stack;
- Depending on the capabilities of the node, more modules (and thus network functionality) can be added. This way, heterogeneous networks can be supported;
- By allowing inter-modular parameter exchanges, cross-layer optimizations are possible. This results in much more energy-efficient protocols;
- Protocol information (such as neighbor tables) can be shared, resulting in better cooperation between protocols and less storage overhead;
- Through the replacement of modules, it is easy to adapt to changing network conditions and future developments.

The proposed framework in [7] is very suited for heterogeneous networks since modules can be added according to the devices capabilities. As such, code updates are more practical because no whole networking layers have to be exchanged, only the relevant modules which contain the needed functionality. Finally, advanced network functionality such as QoS is more easily supported. Therefore, a modular approach is a very promising candidate to be used for a reconfigurable architecture.

6 Additional Challenges

In this paper, several possible architectural and protocol ideas have been given. However, it is also clear that a lot of other challenges and obstacles need to be tackled before symbiotic networking is possible. In the following, a non-exhaustive list of additional challenges that need to be addressed is given.

- Attention should be given to security and authentication, especially regarding the interaction between networks. Provisions should be supported to manage which networks can share their services, resources and infrastructure with each other. Further, authentication should be supported. A part of the network can be open for public use, another part is restricted. Different keys can be used that give access to a certain set of functionalities, i.e. another network may use the location information in the network, but may not use the processing capacity of the nodes. A distributed key-management should be used which is independent of a fixed infrastructure [27, 34].
- Not only should networks be able to seamlessly connect with each other, services should be uninterrupted when a symbiotic network disconnects. This involves a handover mechanism.
- The use cases in Sect. 3 show that for many applications the speed of detection might be a major issue. If the IEEE 802.15.4 networks are used, beacons can be spread as far as 256 s [14]. Even when scanning all 16 channels at once, this delay is unacceptable for critical services such as accident warnings. As such, the extension of existing MAC protocols may not be sufficient, but dedicated MAC protocols may be required to enable symbiotic networking (see also Sect. 4.1).
- Symbiotic networking should be transparent to higher level applications. Symbiotic networking can be used for enabling high level concepts such as Virtual Private Ad-hoc Networks [13] or Personal Networks [2]. These concepts currently set up overlay networks over heterogeneous networks, using the intermediate networks mainly for bridging purposes without supporting any optimizations. Symbiotic networking can be used to transparently optimize the intermediate networking resources without affecting the behavior of higher level concepts.
- Different networks might use different addressing schemes. There should be support for address translation between the networks, or develop self-adopting network addresses. For transparency reasons, only the negotiation gateways should be aware of the address mapping.
- Quality-of-Service metrics should be translated between the symbiotic networks. Exact translation is not always possible as one of the networks could have less capable nodes.

7 Summary

The merging of wireless and wired networks of the same or of different technologies and thereby introducing strong cooperation in routing and services is a completely new idea. It offers additional functionalities compared to existing independently operating wireless networks. In many projects, first efforts have been made to support a limited form of cooperation, thereby clearly indicating a strong need for a more advanced cooperation. Current research mainly focuses either on the physical layer (hereby being unaware of the services on the higher layers, e.g. network & service overlays) or on higher layers (ignoring the possible interference at the lower layers). Therefore, no global optimum can be reached and current solutions are not at all widely applicable. Furthermore, no standardized method currently exists for the exchange of information or the discovery of services between networks.

Cross-layering (supporting the interaction between different layers of a wireless node) has been a hot topic for quite some time. Furthermore, cooperative networking (cross-node) is becoming popular as well, and can be considered as an interaction between different nodes of the same network. The logical and innovative evolution is to combine the advantages of both methods: to support cooperative networking over all layers between different nodes of the same network, in order to obtain even better networking optimizations. However, in this article, we aim for a more disruptive solution: symbiotic networking should support optimizations over all layers of nodes in the same network (cross-layer + cross-node) as well as over all layers of nodes in different networks (cross-layer + cross-node + cross-network).

To this end, we have proposed a cross-network cooperation strategy called DiNS. It consists of three consecutive phases: *Di*stributed Network Discovery, *N*etwork Binding and *S*ervice Convergence. At the end of these phases, we can truly speak of a symbiotic network. In each phase, we have described several necessary steps and challenges that need to be taken as well as given guidelines for designing relevant protocols. In addition, we presented a modular node framework that supports cross-layer interactions and supports a reconfigurable architecture leading to an easy adaptation of the symbiotic protocols.

Symbiotic networks focus on getting better performance, not only at the node level, but also over the whole network in terms of energy efficiency, reliability, QoS and so on. Due to the possibility of globally optimized solutions, the introduction of symbiotic networks is an innovative step for advanced cooperation between co-located (wireless) networks.

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