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A Survey on Dependable Routing in Sensor Networks, Ad hoc Networks, and Cellular Networks

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Abstract

The class of wireless and mobile networks features a dissimilar set of characteristics and constraints compared to traditional fixed networks. The various dimensions of these characteristics/constraints strongly influence the routing system, which is often regarded as the glue of a network. We introduce the concept of routing dependability describing the trustworthiness of a routing system such that reliance can justifiably be placed on the consistency of behavior and performance of the routing service delivered. We investigate this concept by analyzing the basic characteristics of various networks. Subsequently, we derive the most important attributes and impairments that contribute to routing dependability in sensor networks, ad hoc networks, and infrastructure-based cellular networks. Departing from state-of-the-art network designs, we extend our survey to cover future network architectures as well. We finish by briefly investigating possible directions and means that allow mitigating the deprivation of dependability.

1. Introduction

Mobile communications and wireless networking technology has seen a thriving development in recent years. Driven by technological advancements as well as application demands, various classes of communication networks emerged. In this paper, we are particularly interested in sensor networks, ad hoc networks, and cellular networks, each of which class represents a solution to important chapters in the mobile and wireless communications challenge.

1.1. Sensor Networks

Sensor networks for the collection, fusion, and communication of environmental information are considered to have an outstanding potential for research and application [1]. Basically, sensor networks are defined by the combination of miniaturized sensors with communication technology.

Possible applications for sensor networks include the measurement of temperature/humidity [2], the collection of pollution data, the monitoring of weaknesses in building structures, and the detection of chemical agents, to name a few. A main advantage of distributed and collaborative measurements includes the non-obstrusiveness and the increased accuracy of the data collection [3]. These applications demand for smart but cheap sensors, which operate self-organized even under harsh environmental conditions.

Currently, sensor networks are considered to evolve towards so-called "smart dust" if technological advance permits such miniaturization [4]. However, severe limits, for instance, in energy supply, costs, maintenance of once deployed sensor nodes and reliability of operation persist. These and other limits are especially important for the communication aspects of sensor networks as we show later.

1.2. Ad hoc Networks

The visions of untethered communications and pervasive computing make a strong case for the self-organizing operation of mobile and wireless nodes within ad hoc networks. Possible civilian application domains of such networks include inter-vehicular communications [5], disaster recovery, multimedia home entertainment, and zero-configuration personal area communications. Furthermore, there are few proposals for wide area ad hoc networks [6].

All these applications have certain demands in common: either there is impromptu need for communication, or the absence of infrastructure commands the network to be fashioned from whatever resources are immediately available. Moreover, the autonomous and cooperative operation is inherent to the network nodes, which are terminals (end systems) and routers (intermediate systems) at the same time.

However, the scope and features impose constraints on ad hoc network operation such as, for example, limits for network size, high topology dynamics, unpredictability of system characteristics, etc.

1.3. Cellular Networks

Enabled by cellular telecommunication networks, the success of mobile communications has been second to none—according to [7] the number of mobile subscribers surpassed the one of fixed networks in early 2003. Until now, the number one application of cellular networks has been personal voice communication, which has been also reflected in the network development. Application demands for these networks include a high quality of service as well as a high geographical coverage. These demands are usually addressed using hierarchically designed and centrally managed infrastructures [8]. Emerging market opportunities and the success of Internet applications such as electronic mail and the World Wide Web introduce various research challenges to cellular networks. We observe a convergence of services while at the same time the heterogeneity of network technologies prevails. These concerns are partially addressed in the International Mobile Telecommunications 2000 (IMT-2000) framework.

The limitations of cellular networks lie in the necessity for an expensive infrastructure. Moreover, the flexibility of the network is highly restricted due to its centralized management and control [9].

1.4. Future Networks

The Internet has never been designed to support the heterogeneity, dynamics, and mobility it faces today with the integration of a wide range of wired and wireless technologies. Satellite and mesh networks extend the Internet's core of high speed fiber optics with a highly configurable wireless infrastructure, allowing service mobility in different scales ranging from mobile devices [10] to mobile networks [11]. The increasing dynamics and heterogeneity take their toll on breaking up trust and service relations of previously well controlled static networks. Moreover, the routing transparency of the end-to-end paradigm is broken by enabling middleboxes [12].

These problems are addressed in the proposed future architectures for the Internet (see, for example, [13], [14], [15], and [16]). The underlying concept is to separate the identity resolution from the forwarding mechanism [17] to reestablish network layer transparency for services on top of heterogeneous networks architectures. Other proposals suggest competitive mechanisms for the routing system to speed up development of non-functional services [18] [19]. Limitations of the proposed future Internet architectures cannot be foreseen in detail yet.

Proposals for future network architectures also exist for the telecommunication network domain. One trend is the combination of multihop strategies and/or variable topology concepts with current cellular architectures in order to leverage the capacity of wireless access networks (see [20], [21], [22], and [23]). However, these architectures exhibit various problem areas in the context of routing such as, for example, a lack of understanding in the fundamental principles of reliability, robustness, and predictability in performance.

1.5. Motivation

The aforementioned networks are mostly routing networks building on top of the Internet's paradigm of a connectionless and packet-switched communication. Cellular networks currently mostly follow a circuit-switched approach but are evolving towards packet-switched paradigms. Thus routing remains an important research challenge within all of the above networks.

However, designers and developers of routing architectures and protocols—driven by the market which demands visible features in the application domain—often neglect fundamental concepts and principles such as dependability, availability, and reliability. Decoupling of these fundamental concepts from high-level goals typically result in only inferior routing systems. For example, the important yet complex high-level concept of quality of service is likely to fail if the dependability of the underlying network cannot be guaranteed adequately. In the end, the envisioned applications may fail, because the network is not able to deliver an adequate service.

From an end-to-end perspective, routing systems based on Internet technology act as a black box which delivers a transparent routing service to the end systems. In this work, we are especially interested in breaking the seal of this black box and dissecting its behavior. In particular we are to study the effects induced on the dependability of the routing system with respect to the characteristics of mobile and wireless networks.

1.6. Outline

In Section 2, we introduce our working definition of routing systems and dependability. We extend these definitions to precisely describe the concept of routing dependability in Section 3. Section 4 is devoted to a study of the most important characteristics of sensor networks, ad hoc networks, cellular networks, and future network architectures, respectively. Here, we also refine our concepts based on the results from Section 3. We finish by drawing conclusions and pointing to potential future work in Section 5.

2. Working Definitions

This section establishes our working definitions for the terms *"routing system"* and *"dependability"*. The definition of a routing system determines the boundaries of our investigation on an abstract level. Departing from its non-technical meaning, we briefly describe the general concept of dependability.

2.1. Routing Systems

The International Telecommunications Union (ITU) defines the process of routing to be [24]:

Definition (1). *"(a)* ***Routing****—the process of determining and using, in accordance with a set of rules, the route for the transmission of a message or the set-up of a call. The process ends when the message or the call has reached the destination location." and "(b)* ***Routing****—a qualification implying the above process, for example: call routing; message routing; traffic routing."*

In our case the term routing system may best be defined using an end-to-end perspective which consists of a source and destination node. To allow for communication, the delivery of messages is a logically required architectural functionality of the network (intermediate system). We connote this with the term *routing* and the functional components of the system as *routers*. The process of routing consist of (a) a service for *identity resolution (resolution of the address where an uniquely identifiable node can be reached)* and (b) the capability to *forward (transport)* messages through the system. Let us define a routing system:

*Definition (2). "A **routing system** delivers messages from a source node to a destination node by means of networked intermediate nodes **(routers)** which implement the functional process **(routing)** of identity resolution and message forwarding."*

From a systems perspective we can mainly distinguish two types of service provided by the network and routing system, respectively [25]:

- The service can be *reliable* or *best effort* (unreliable, datagram). A reliable service model guarantees the delivery of packets without duplicates and in order. A best effort network delivers the packets as they arrive at the destination.
- The service can be *connection-oriented* or *connectionless*. Connectionless communication uses individual packets which are transmitted independently. Connection-oriented communication first establishes a path which is subsequently followed by all messages.

In the remainder of this work, we use the term routing system synonymously with the unreliable and connectionless Internet service, which is the subject of our investigation. Despite the presence of various cross-layer interactions, especially with regard to lower layers, we consider the routing service to be a network layer discipline only. The datagram routing in the Internet is transparent to the end systems and as a consequence the routing system/network is often treated as a black box. However, the black box model is not sufficient for the investigation of routing dependability [25]. Hence, we aim to have at least a translucent view into the routing system. Our perspective also distinguishes between the data plane (end-to-end traffic between source and destination) and the control plane (control traffic between individual routers) of the routing system.

The individual strategies and procedures to implement routing may vary. Usually one distinguishes between static routing algorithms or strategies and routing protocols that capture and distribute the dynamics of the routing system. Figure 1 visualizes two possible instantiations of a routing system employing a single path routing strategy and a multipath routing strategy, respectively. The former strategy models today's prevalent Internet routing paradigm and is depicted with the black packets. The latter one is pictured with gray packets. For both cases, we assume the routing

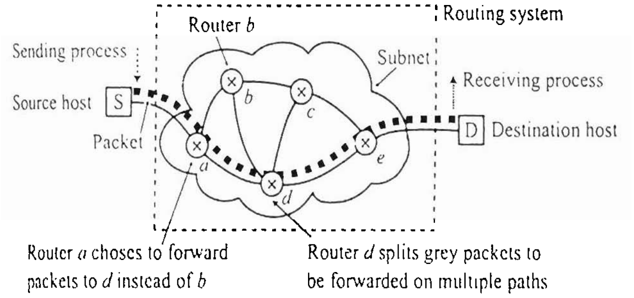


Figure 1: Instantiation of a routing system for a single path and a multipath routing strategy, respectively. We give the most important entities and define the boundaries of the routing system as far as concerned in our work.

decisions to be decentralized and distributed, which, however, does not limit the generality of our work.

2.2. Dependability

The root of the adjective *"dependable"* is dated back to 1735 in [26], its meaning being *"reliable"*. In modern written and spoken english the meaning of dependable has slightly evolved and is commonly referred to as [27]:

*Definition (3). "**Dependable**—worthy of reliance or trust." and "**Dependable**—consistent in performance or behavior."*

These definitions are of very interest for defining the notion of dependability in a technical sense. They emphasize the value and importance of dependability; a failure in dependable operation may lead to the failure of the overall system. Moreover, the consistency of performance and behavior conveys the intention of dependability to be measured and guaranteed in a more technical manner.

To be able to qualify and quantify the dependability in the context of technical systems it is necessary to focus on the individual characteristics defining a particular system. In the remainder of this paper we investigate routing systems in various classes of networks.

2.3. Trust

As already stated in Def. (3), dependability is closely coupled to the concept of trust which we define to be:

*Definition (4). "**Trust**—the confidence or reliance on attributes or the expectation in certain behavior."*

For routing systems, the concept of trust conveys aspects from an end user as well as network perspective. In our investigation we focus on the latter aspects. In static environments, trust relationships may be preconfigured and controlled from the network operator. In contrast, the notion of trust is implicitly subjective and dynamic in nature in networks with heterogeneous and/or autonomous nodes operating in distributed and decentralized fashion. Here, each node can adapt its trust level based on different factors like prior knowledge and context information which are dynamically increased or decreased by collaboration and observation of each node.

3. The Concept of Routing Dependability

In the following we derive a conceptual model of *routing dependability*, which is the core of this work. We first define the concept theoretically in this section while the next section embeds our theoretical basis in the context of real networks. For the domain of routing networks we discuss the most prominent definitions which are based on work from the International Telecommunication Union (ITU), the Internet Engineering Task Force (IETF), as well as various research in this area.

3.1. Dependability in Telecommunication Networks

For traditional telephone networks (PTSN) and integrated service networks (ISDN), the ITU defines concepts related to quality of service and network performance including dependability to allow for planning, provisioning, and operation of telecommunication networks in [28]. The basic model for performance concepts of the ITU has four major building blocks, which are related to our work: quality of service, serveability, trafficability performance, and dependability. *Quality of service* (QoS) is the most abstract concept in the model and describes the satisfaction of a *user* of the *service*. The service related primitives of QoS are described with the concept of *serveability*, which includes the components *service availability performance*, *service reliability performance*, and *service integrity performance*. Ref. [28] defines QoS to be:

Definition (5). *"**Quality of Service**—the collective effect of service performance which determine the degree of satisfaction of a user of the service."*

To be able to maintain a certain QoS level, the perspective of items (infrastructure components) is described in the network performance part of the diagram. The *trafficability performance* building block acts as a technical description of the ability of an infrastructure component to deliver a certain performance level. Finally, the foundation of the aforementioned concepts is given by the concept of *dependability*, which is further refined into *availability performance*, *reliability performance*, and two *maintainability* related blocks. These concepts are the most important ones for the context of our work and defined in as follows [28]:

Definition (6). *"**Trafficability performance**—the ability of an item to meet a traffic demand of a given size and other characteristics, under given internal conditions."*

According to [28], dependability is the key performance measure for this concept and can be defined as follows (see Figure 2 for a visualization of ITU's QoS model):

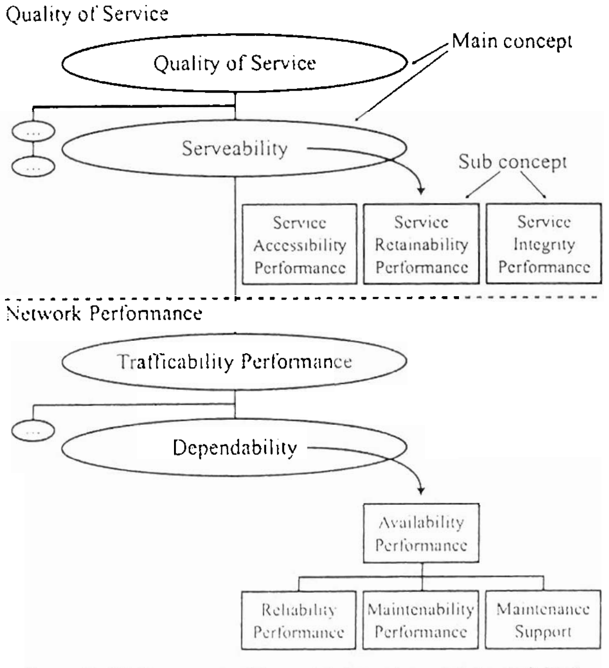


Figure 2: ITU's concept of dependability, adopted from Ref. [24].

Definition (7). *"**Dependability**—the collective term used to describe the availability performance and its influencing factors: reliability performance, maintainability performance and maintenance support performance."*

Definition (8). *"**Availability performance**—the ability of an item to be in a state to perform a required function at a given instant of time or at any instant of time within a given time interval, assuming that the external resources, if required, are provided."*

Definition (9). *"**Reliability performance**—the ability of an item to perform a required function under given conditions for a given time interval."*

We exclude the maintenance-related performance, that is, the restoration of the function by means of maintenance, since our focus is on the technical rather than the operational aspects of dependability. In the same context the terms *availability* and *reliability* are used as the respective performance measures. Unfortunately, the ITU definitions are tightly coupled to operational considerations as well as to resources and facilities. As a consequence they are not generally applicable to scenarios outside the telecommunication sector.

3.2. Dependability in the Internet

Likewise in telecommunication networks, we perceive dependability in the Internet to be an enabler for higher level concepts such as, for example, QoS. However, Def. (5) cannot be easily interpreted in the technical domain. A technically more precise definition of QoS was introduced by Schmitt in [29]:

Definition (10). *"**Quality of service (QoS)** is the well-defined and controllable behavior of a system with respect to quantitative parameters."*

The current Internet lives without QoS, which is in part due to the complexity of the QoS concept. Moreover, the basic routing of the Internet can hardly be judged dependable. The predecessor of the Internet, the ARPANET suffered from catastrophic failures, which could only be repaired with manual interaction (see, for example, [25] for details). Based on this experience, the Internet community decided to require routing protocols to be self-stabilizing. While this basic criterion is quite important, there is only few work devoted to dependable network design. These existing work mainly focuses on routing security and operational consideration (see, for example, [30]). In [31], the focus lies on routing protocols but excludes the overall routing system explicitly.

The only rudimentary addressing of routing dependability in this community is compensated in part in the research community. The work of Perlman [25] fits excellent in the scope of our work. According to [25], a (routing) network design process should consider the following principles:

Scope, scalability, robustness, autoconfigurability, tweakability, determinism, and *migration*.

In this context, autoconfigurability describes the network's ability to operate in plug-and-play fashion without manual intervention. The goal of robustness is subdivided into four subgoals which are:

- *Safety barriers* which hinder the spreading of faults.
- *Self-stabilization* after the defect or malfunctioning device is eliminated.
- *Fault detection* as an ability of the network.
- *Byzantine robustness* in case of improperly operating components or attacks.

See also Kenyon [32] for a more operational perspective on performance and reliability characteristics of internetworks. There exists other work in the area of smart networks, which focuses on the dependability of the network transport. Helvik in [33] closely relates dependability to the survivability of the core transport functionality even for failure conditions. His results are based on general work in the area of dependability and transferred to the network domain (see Figure 3 for the dependability tree introduced in [34]).

Integrating the aspects of both domains, we define routing dependability to be:

Definition (11). *"**Routing dependability** is the trustworthiness of a routing system such that reliance can justifiably be placed on the consistency of behavior and performance of the routing service it delivers."*

Def. (11) is open enough to embrace all types of networks we investigate. This includes hybrids of different network classes such as integrated hot spots in beyond 3G (B3G) systems. In each network class the dimensions of dependability may vary depending on the inherent characteristics of the network's routing system.

The concept of routing dependability is often overlooked. However, viable solutions for higher-level concepts like network QoS and security are only possible if the groundwork, in particular, sufficient mechanisms to ensure the dependable operation, is laid. Please keep in mind, however, that by definition a connectionless best-effort routing system cannot guarantee the delivery of messages. Here, the transport layer may augment the necessary functionality.

4. Network Characteristics

We have devised the most important concepts in the field of routing dependability in the preceding sections. Here we investigate the characteristics of various classes of networks which is necessary to develop a more concrete and network-specific description of Def. (11).

4.1. Characteristics of Sensor Networks

Sensor networks are one hot topic in communication networks with a large body of related work in the area of sensor networks (we particularly recommend [1] and [35] for general surveys, and [36] for the focus on routing in sensor networks). Application goals often include adaptability and high sensing fidelity. The network should be fault tolerant, energy efficient, and low cost. As a consequence, one faces various trade-offs in designing sensor networks, some of which are also reflected in the design of the routing system. The specific characteristics of sensor networks are:

- *Limited resources* (energy supply, bandwidth, cpu power, memory size, etc.).
- *Restricted manageability* (unattended after deployment, hostile environments, self-configurability, etc.).
- *Large scale* (possibly millions of nodes, rapid deployment, geographical awareness, etc.).
- *Special requirements* (different communication patterns data centric vs. node centric, simplicity, fault tolerance, physical robustness, low cost, etc.).
- *Heterogeneity* (in application, in sensing, in computing, in communications, in connectivity, etc.).
- *Different quality metrics* (sensor fidelity, quality of information, dependability, etc.).

Compared to traditional networks, sensor networks exhibit fairly different characteristics and quality metrics. Because of the high integration of the sensor nodes and the very specific application goals, there is no one size fits all solution but the diversity in characteristics commands the routing mechanisms.

4.2. Characteristics of Ad hoc Networks

In ad hoc networking research the routing system is a very prominent research object (see [37] for a taxonomy of routing protocols). The main directions of research include performance optimizations and scalability issues (see, for example, [38]). Only recently, quality of service and security have also drawn attention. Likewise performed for sensor networks, we are able to derive the dimensions of routing dependability for the case of ad hoc networks based on the predominant network characteristics. Nodes in ad hoc networks are both, terminals (end systems) and routers (nodes). Also ad hoc environments may suffer from harsh constraints. Summarized the characteristic features of ad hoc networks are as follows:

- *Heterogeneity* (in nodes {notebook/pda/mobile phone/artefacts}, in communications, in connectivity, etc.).
- *Mobility* of nodes (speed, direction, predictability of movement, etc.).
- *Wireless communication channel* (broadcast nature, transmission errors, limited range, hidden and exposed terminals, partitioning, etc.).

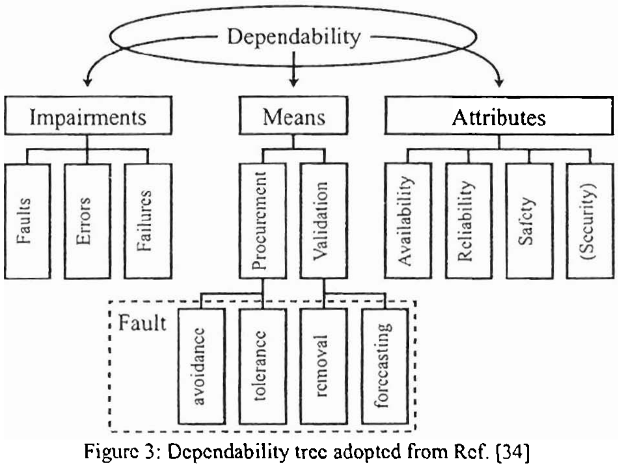


Figure 3: Dependability tree adopted from Ref. [34]

- *Absence of infrastructure* (nodes are both, end systems and routers, need to cooperate, affects scalability, etc.).
- *Open* network without fixed subscribers.
- *Application characteristics* (peer-to-peer, real time, unicast, multicast, geocast, etc.).

The characteristics are dominated by the absence of infrastructure, the highly dynamic nature of the topology, and possible asymmetry in devices or communication channel. Moreover, the system is qualified by the need for cooperative operation of the nodes. Most routing protocols silently assume only well-behaved and cooperative nodes to allow for multi-hop operation of the network, however.

Following, we focus briefly on the aspect of node misbehavior, which we find to be of particular interest. There exist multiple classes of misbehavior, which we derived in [39] we aggregating comparable types of node behavior, while maintaining the analytical tractability of our description of misbehavior:

- *Cooperative nodes*, which comply to the standard at all times.
- *Inactive nodes*, which include *lazy nodes* (unintentionally misconfigured) and *constrained nodes* (energy-constraint or field-strength-constraint, etc.).
- *Selfish nodes*, which optimize their own gain, with neglect for the welfare of other nodes.
- *Malicious nodes*, which inject false information and/or remove packets from the network.

We note that, depending on the degree of non-cooperation the nodes exhibit, selfishness may partially overlap with inactivity. There exist models and simulation studies in previous work to investigate the influence of node misbehavior with respect to the overall routing system [40] [39].

4.3. Characteristics of Cellular Networks

Cellular networks are built around infrastructure components. In traditional telecommunication networks the architecture follows a strictly hierarchical design and network control is centralized. We have a "smart" core and a "dumb" edge (or more precisely a "dumb" access network, which consists of the Node B and the Mobile Equipment). Critical components of the system are highly redundant and determine the notion of routing dependability in cellular networks. The characteristics that influence cellular networks are relatively deterministic compared to sensor networks or ad hoc networks:

- *Mobility* of users and end systems, and *wireless* communication channel.
- *Hierarchical, infrastructure-based* system architecture.
- *"Smart" core* (RNC, SGSN, GGSN).
- *"Dumb" edge* (Mobile Equipment, Node B).
- *Closed* subscriber *network*.
- *Centralized control* of the routing/forwarding system (but routing in the core only, non-routed access network).

The core network of cellular networks faces the same routing challenges as Internet-like architectures, though. Here clearly a trade-off between network control and routing dependability exists. Today's cellular networks are optimized with respect to connection-oriented communication, and the centralized control allows for high dependability. This leaves, however, only few room for optimization using decentralized mechanisms, and the performance of the connectionless data communication in such networks suffers. This effect is biased with the emergence of third generation networks and beyond to support mobile communications. Here we witness a movement towards smart edges and routing networks in the cellular domain. These networks as well as cellular networks based on inexpensive wireless local area network technology exhibit various problem areas, especially in the context of routing. In networks with trusted infrastructure we perceive the network performance aspect of routing dependability of high importance. See [41] for work covering the performance aspects of dependability in future cellular architectures which support packet-switched paradigms under the constraints of realistic mobility models.

4.4. Characteristics of Future Networks

Future networks embrace a wide range of wireless and wired technologies at the edge and in the backbone. The routing system of the resulting heterogeneous internetwork is challenged by mobility and recurring changes in topology. A convergence of cellular telecommunication networks with the Internet can be anticipated if the future architectures adequately supports mobility. We also foresee the integration of capabilities of ad hoc networks by means of gateways/smart edges and to some extend by an adaptive core. This does not only allow dynamics in the end systems, but also in the network's peripheral components. The same hold from a service perspective.

The characteristics of future network architectures are:

- *Heterogeneity* (in access {wireless/wired}, in protocols, in components {switches/routers/gateways}, in services {packet-switched/circuit-switched}, in algorithms, etc.).
- *Open and scalable infrastructure* (extensibility, well known interfaces, etc.).
- *Extreme network dynamics* (static/mobile networks and devices, overlay networks, multi-homing, etc.).
- Nearly *unlimited physical resources* in parts of the network (memory, storage, bandwidth, energy)
- Sophisticated *control* and *management capabilities* (in services, in protocols, in algorithms, etc.).
- *Diversity of application characteristics* (peer-to-peer, client-server, real-time/streaming/interactive/background, unicast/multicast/anycast, etc.).

Summarized future networks have to cover an incredibly huge spectrum of functional and non-functional requirements. Of particular importance is their ability to address services and data instead of hosts, making the network topology itself transparent. The design of routing systems has to keep up with the resulting dynamics. Although the visions of future networks are clear and widely shared, the consequences to dependability and performance aspects of the routing system are currently not in the focus of research.

4.5. Summary

We identified the most important characteristics of various classes of networks and analyzed these with respect to routing dependability in the previous subsections. As a synopsis, the dimensions of network control and topology dynamics can be identified to be of utmost importance:

- The dimension of *network control* includes the routing architecture and strategy. The surveyed systems cover the full range from strictly hierarchical and centrally controlled cellular networks to spontaneous formation of ad hoc nodes operating autonomously. While the network architecture and design can be seen as a factor which is of long-term relevance, traffic engineering is considered to be a medium-term objective while adaptive routing decisions is a short-term issue.
- The dimension of *topology dynamics* covers aspects such as, for example, user and end system mobility. It is obvious that the topology dynamics are directly related to the dynamics of the routing system itself, which in fact determines the perceived network dependability. Moreover, the wireless nature of the communication channel contributes to the routing system in ad hoc and sensor networks. The possibility to run out of energy and the vulnerability of sensor or ad hoc nodes to environmental conditions or adversaries is of importance as well. Moreover, in autonomous systems without centralized control, the misbehavior of individual network nodes may cause fairly complex problems.

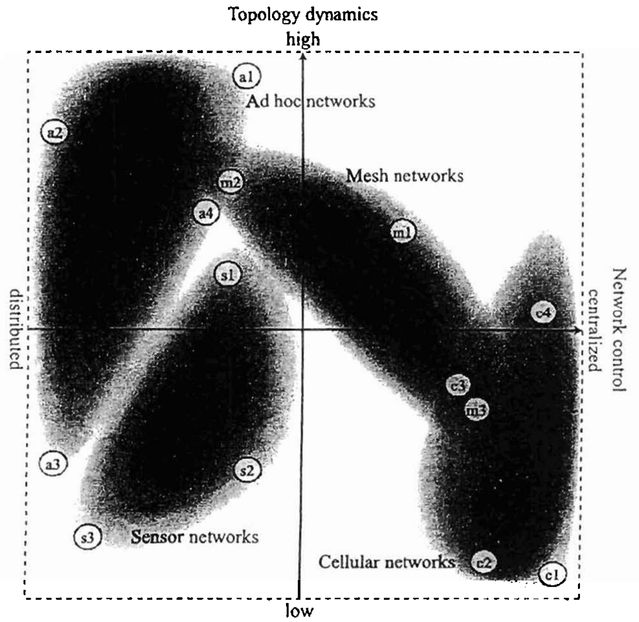
There clearly exist orthogonal dimensions such as the autonomy and heterogeneity of end systems or nodes, which also contribute to the problem as such. We do, however, limit our discussion to the core of routing systems, which we specify by network design, routing strategies, and node behavior. See Figure 4 for a graphical representation of the dimensions of the various classes of networks. The shapes for the network classes are based on sample networks belonging to the respective class and have been discussed in a panel of experts. The preceding discussion has shown the need to tailor future routing architectures as well as protocols to fit tightly and provide the basic concept of routing dependability.

5. Conclusions

The communication service provided by the Internet and telecommunication networks to support user mobility is about to reach nearly ubiquitous coverage. These networks are often routing networks. However, designers and developers of routing architectures and protocols often neglect fundamental concepts and principles such as, for example, dependability, availability, and reliability. Driven by the market they solely focus on more advanced goals and features. However, decoupling of these fundamental concepts from high-level goals typically result in only inferior routing systems. For example, the important yet complex high-level concept of quality of service is likely to fail if the dependability of the underlying network cannot be guaranteed adequately.

We have discussed the concept of routing dependability in mobile and wireless networks in detail. Starting with general definitions we set the boundaries of our study. We derived the concept of routing dependability for sensor networks, ad hoc networks, as well as cellular networks. In particular, the promise of sensor and ad hoc networks is built upon the premise of cooperation among nodes. Previous work has shown the network frailty in the absence of such a cooperation [39]. Moreover, the variability in topology in ad hoc networks and the harsh environmental conditions in sensor networks impose constraints on the routing system. This deprivation of dependability in the routing system is perceived to be one factor hindering sensor and ad hoc networks to cross the chasm between research prototypes and real world systems reaching a critical mass of deployment.

In traditional cellular networks, the highly redundant infrastructure in combination with centralized control mechanisms provides for a solid foundation for the routing system. Here a trend towards variability in topology can be witnessed while at the same time network control reaches some autonomy. The challenge in these networks is to maintain the current level of dependability while optimizing the network operation by means of smart network control.



Ad hoc networks
(a1) Vehicular network
(a2) Spontaneous collaboration
(a3) Multimedia home network
(a4) Disaster recovery network

Cellular networks
(c1) 2G/3G Telecommunication network
(c2) B3G Telecommunication network
(c3) Hotspot network (WLAN)
(c4) Multihop cellular

Sensor networks
(s1) Smart dust
(s2) Environmental data collection
(s3) Building automation/monitoring

Mesh networks
(m1) Community mesh network
(m2) Taxi cab network
(m3) Meshed wireless backbone

Figure 4: Classification of the surveyed networks with respect to network control and topology dynamics. Please note that emerging technologies such as, for example, mesh- or B3G networks may even extend the concepts shown.

Our survey provided definitions and insights which assist in developing and operating more dependable routing networks. We perceive the necessity to establish mechanisms which allow for engineered dependability in the discussed types of networks, similar to traditional telecommunication networks. There is no panacea for dependable routing; however, in parallel with the trend towards autonomous and highly dynamic systems, we envision the establishment of routing dependability to be also part of a self-organizing process. In the area of ad hoc and sensor networks, this translates into mechanisms to establish a distributed and self-organizing notion of trust in the next step of our future work. In the area of future cellular networks we perceive the investigation of smart algorithms to leverage the full capabilities of the underlying architectures, while maintaining an adequate level of dependability, of high importance.

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