Advances in Emergency Networking

Maurits de Graaf, Hans van den Berg, Richard J. Boucherie, Herman Elfrink, Sonia Heemstra de Groot, Roland de Haan, Arjan te Marvelde, Jan–Kees van Ommeren, Frank Roijers, Jan Stemerdink, Erik Tromp

Abstract- Crisis situations require fast regain of control. Wireless ad-hoc networks will enable emergency services to act upon the actual status of the situation by retrieving and exchanging detailed up-to-date information. Deployment of high-bandwidth, robust, self-organising ad-hoc networks will therefore enable quicker response to typical what/where/when questions, than the more vulnerable low-bandwidth communication networks currently in use. This paper addresses a number of results of the projects AAF (Adaptive Ad-hoc Freeband communications) and Easy Wireless that enable high bandwidth robust ad-hoc networking.

I. INTRODUCTION

In emergency situations, it is of vital importance for rescue personnel to obtain an accurate and consistent picture of the situation, and to regain control and co-ordination on the shortest possible notice. This prevents further escalation, minimises the number of casualties and restricts the damage. The communication systems that are available now for rescue services lack crucial functionalities. They suffer from high vulnerability due to the fact that they rely on a fixed infrastructure and lack of self-organization capabilities. Moreover, they do not support multimedia applications asking for high quality communications and/or high bandwidth. This paper presents some results of the project AAF ('Adaptive Ad-hoc Freeband communications) [1] and the ITEA Easy Wireless project (EW) [2]. These are introduced below.

A. *Adaptive Ad-hoc Freeband communications (AAF)*

Especially in an emergency situation, data communications require a significant amount of radio spectrum, while at the same time this is a scarce resource. Today's approach divides the radio spectrum into many small bands, resulting in sub-efficient spectrum usage. However, the FCC (Federal Communications Commission) is pursuing 'Cognitive Radio' [3] as a new paradigm in spectrum utilization. Cognitive Radio is defined as a radio that changes its behaviour based on interaction with the environment. The AAF project focuses on a key element: search for under-utilised spectrum and (rapidly) adaptation of transmissions to exploit these free spectrum opportunities. These new developments on the physical layers obviously also impact the higher layers of the protocol stack.

B. *Easy Wireless (EW)*

Ad-hoc networks are particularly suitable in situations where a fixed communication infrastructure, wireline or wireless, does not exist or malfunctions e.g. due to a disaster. Due to the lack of centralised control and the variable topology, several significant technological challenges in the support for Quality of Service (QoS) in ad-hoc networks remain. **Support for QoS** and **service continuity** for mobile users are the central themes of the use case 'emergency services' of the ITEA Easy Wireless (EW) project.

C. *This paper*

In this paper, we present the results of the projects AAF and EW without further distinction between the projects. Section II presents extensions to the well-known OLSR protocol for ad-hoc networking. These extensions optimise the routing protocol for the fact that wireless links with different properties (link speed, error ratio, type) will be discovered by the frequency scanning mechanism. In Section III the capacity gain that can be obtained by using

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Maurits de Graaf, Arjan te Marvelde and Erik Tromp are with Thales Divion Land & Joint systems in the Netherlands, P.O. Box 88, 1270 AB Huizen, Netherlands, +31 35 5248 149; fax +31 35 5248 343, Maurits.deGraaf@nl.thalesgroup.com.
Herman Elfrink, Sonia Heemstra de Groot, Jan Stemerdink are with WMC (Twente Institute for Wireless and Mobile Communications), sonia.heemstra.de.groot@ti-wmc.nl.
Richard J. Boucherie, Roland de Haan, Jan–Kees van Ommeren are with the University of Twente, R.J.Boucherie@utwente.nl.
Hans van den Berg and Frank Roijers are with TNO, J.L.vandenBerg@tno.nl.

nodes with multiple wireless interfaces and channels is investigated. In the architecture of an emergency network the vehicle nodes will often have multiple wireless interfaces. For the support of the Quality of Service for time and loss critical services, the IEEE 802.11E QoS is often regarded as a solution. The capabilities of this mechanism to realise service differentiation in an ad-hoc situation is investigated in Section IV in an ad-hoc situation. Section V analyses the influence of mobility on the capacity of an ad-hoc network. Finally, Section VI presents the conclusions.

II. PATH COMPUTATION AND COST MEASUREMENT ADAPTATIONS TO A ROUTING PROTOCOL

Within an ad-hoc emergency network, nodes can join, leave and move around on the fly. There can be multiple links of different type between nodes, e.g. a wired and a wireless link. OLSR is one of many available route discovery protocols which are optimized for MANETs. In a standard, RFC-compliant OLSR implementation [4], a path from source to a destination is calculated by minimizing the number of hops. Practical experiments [5] show that paths, which are established this way, have a low quality, especially if the hops are wireless. The main reason is the fact that often the neighbor discovery process is fooled by transient link availability with nodes that are too distant for reliable communication to take place. The ETX (expected transmission count) extension of OLSR ('OLSR-ETX'), as found on www.olsr.org, takes into account the packet loss ratio on a link in the calculation of an optimal path through the network. However, OLSR-ETX does not take into account other characteristics which may be important, such as the bandwidth of a link. In a mixed wired/wireless network, wired links may be preferred over wireless links. The ETX metric cannot be easily adopted to achieve this.

Within AAF and EW, the OLSR-ETX extension has been taken a step further to take into account the characteristics of the available communication links. This so-called 'link cost extension of OLSR' involves three steps: (1) Determination of the link cost; (2) Selection of the MPRs (Multipoint Relays); (3) Calculation of the optimal paths. The remainder of this section will discuss each of these steps.

A. *Determination of the link cost*

The link cost is calculated as follows:

$$C = Q (T + W/S), \tag{1}$$

Here Q denotes the ETX-value as measured by the OLSR-ETX extension, T denotes a scalar related to the medium type (which can for example be wireless, or optical fibre). T can be interpreted as the additional amount of links of a preferred type (low T) that we are willing to traverse extra to avoid a link type that is less preferred (high T). S denotes the medium speed. W is a weight factor that indicates the importance of the medium speed in relation to the medium type. When T is chosen to be the additional time needed to access the medium (e.g. radio access), C can be interpreted as a 'per-bit transmission time', which is proportional to the 'per-packet transmission time'. Since transmission time adds up as packets hop through the network, the formulated link cost is an additive metric.

Most current-day router products offer only the possibility to pre-configure the cost of a given link. To deal with the highly versatile network environment in an emergency situation, we added a function to measure the link speed (bandwidth) and, as an additional feature, to determine the link type (wired or wireless).

B. *MPR selection*

MPRs are selected nodes which forward broadcast messages containing topology information. OLSR attempts to minimize the number of MPRs. The heuristic for the selection of multipoint relays in the standard OLSR does not take into account other metrics. Consequently, the path calculated between two nodes using the known partial topology may not be the best in terms of link quality. Therefore, we extended OLSR in such a way that each node takes into account the link cost in the selection of its MPRs. This leads to the following 'link-cost' MPR selection heuristic:

For each node that can be reached via less than 2 hops, find the set of all paths with the same, lowest path cost. Call this set the 'set of best paths'.

1. *If the ‘set of best paths’ contains a 1-hop path, consider the node to be a 1-hop neighbor. No MPR needs to be selected for this neighbor.*
2. *Otherwise (the ‘set of best paths’ consists only of 2-hop paths):*
    - 2.1 *If there is exactly one path with the lowest cost, choose the 1-hop neighbor in that path as MPR.*
    - 2.2 *If there is more than one path with the same lowest cost, then choose the MPR that covers most 2-hop neighbours.*

Compared to other methods (e.g. [6], [7], [8]), our heuristic takes into account that a 2-hop neighbor may be better reachable via a direct 1-hop link, or vice versa. Moreover, it specifies which MPR to select in the case that multiple paths with the same (lowest) cost are available.

C. Optimal Path Calculation

The last step in the routing process is to calculate the optimal paths. Standard OLSR uses Dijkstra’s algorithm where all links are assigned the value 1 (edge weight 1). In our approach (1) we use C as the metric to quantify the link costs suitable for use in Dijkstra’s algorithm.

III. MULTI-RADIO NODES

In a traditional ad-hoc mesh network the capacity is severely limited by the fact that all communications take place through the same frequency channel. Multiple successful transmissions cannot occur simultaneously within the same area without interfering with each other; at any given time, only one correct transmission can take place in an interference domain. This capacity limitation can be relieved by using multiple non-overlapping frequency channels; simultaneous transmissions over different channels in the same area will not interfere with each other (see e.g. [9] for a survey).

One convenient way to realize multi-channel mesh networks is to equip nodes with multiple off-the-shelf IEEE 802.11 network interface cards (NICs) using existing standards. These multiple radio interfaces can each be tuned independently to different channels, selected from a pre-defined channel set. A prototype multi-radio node was developed that can be equipped with up to 4 NICs; a schematic diagram is shown in Fig. 1. It includes the Forwarding Layer for Meshing (FLAME, [10]), and a Multi-Channel MAC (MCM) layer to multiplex the transmissions through the different NICs. It optionally includes a scanning radio (in fact, that is one of the NICs) which is dedicated to the task of scanning the neighborhood for other nodes and the channels they are using.

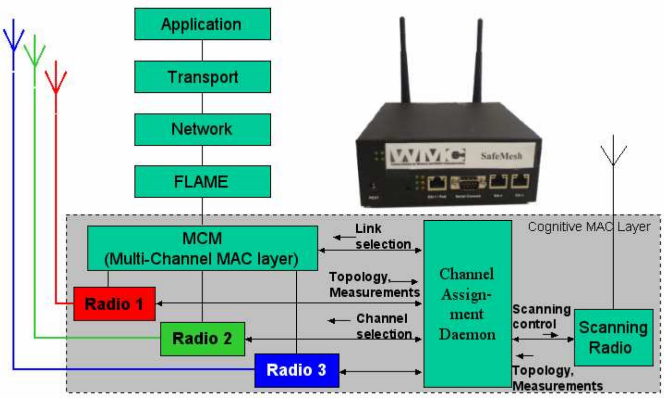

Fig. 1. Prototype multi-radio node

On each node a channel assignment algorithm is responsible for minimizing the internal interference and congestion of the network, through the proper selection of the channels on each of the radio interfaces. Based on local information about the node’s neighborhood, this algorithm selects the channel combination that has the smallest overlap with the neighbors’ channels. A simulation program of layers 1 and 2 was created to facilitate the design and evaluation of various channel assignment algorithms, and to evaluate the throughput that is achieved with various numbers of radios per node, and with various numbers of channels. As a performance measure, this simulator evaluates the (average) number of successful transmissions that can take place simultaneously in the entire network. In interactive mode the simulator shows the network graph on the screen, as well as transmissions, and transmission statistics; the user can alter various node and network parameters through a control panel.

Various simulations were run to study the impact on the network throughput of the number of radios per node and the number of channels. Fig. 2 shows the results of a simulation experiment with a network of

100 randomly moving nodes, with random channel selection. The curves represent the network's average aggregate throughput (the number of simultaneous successful transmissions) as a function of the number of channels, for 2, 3 and 4 radios per node, respectively.

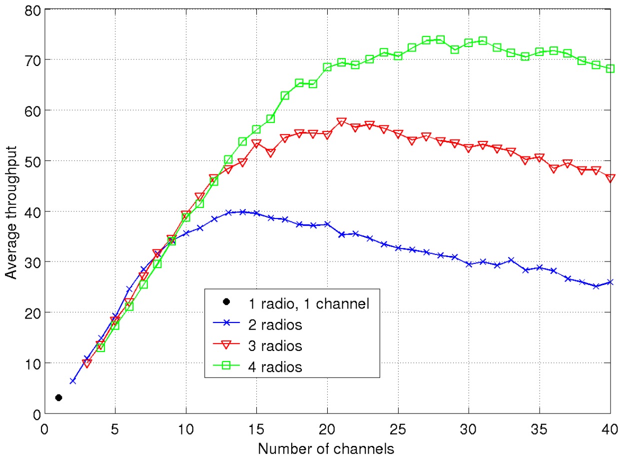

Fig. 2. Multi-channel network throughput

For a low number of channels, the throughput increases almost linearly with the number of channels, independently of the number of radios. The decline at a high number of channels is partly caused by the loss of connectivity as the probability of nodes lacking a common channel increases with the number of channels.

IV. QOS-PROVISIONING IN IEEE 802.11 AD-HOC NETWORKS

Today's wireless ad-hoc networks are mainly based on IEEE 802.11 [11] technology. These networks have difficulties in meeting the requirements of real-time and broadband applications, e.g. voice, video and high speed data transfer. This is due to the characteristics of ad-hoc networks such as dynamically varying network topology, the lack of central coordination, error prone shared radio channel and the hidden terminal problem. In order to sup-port the services, Quality of Service (QoS) provisioning capabilities are required. The 802.11E standard [12] enables QoS-differentiation between applications on a per-node basis, we refer to this as packet-level scheduling. An alternative approach to obtain QoS is node-level scheduling; certain nodes are favored over other nodes. In this section numerical results are presented, illustrating both types of differentiation; the results are obtained by an ad-hoc network simulation tool.

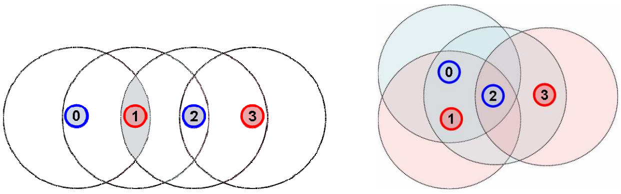

Fig. 3. Left: 4 node ad-hoc chain network. Right: Ad- hoc network with a bottleneck node (node 2).

First we present a relatively simple ad-hoc network, a so-called chain topology, giving insight into the benefits of QoS/differentiation of IEEE 802.11E. In this scenario (cf. left graph of Fig. 3.) the first node initiates two flows, which traverse the entire chain, that have different QoS requirements and are treated with different priorities by the nodes. Fig. 4. presents the throughputs, for different number of hops. For a single hop we see that the throughput of the high priority flows is three times higher than the low priority flow. For longer chains (in particular, more heavily-loaded hops) the differentiation capabilities of IEEE 802.11E are less.

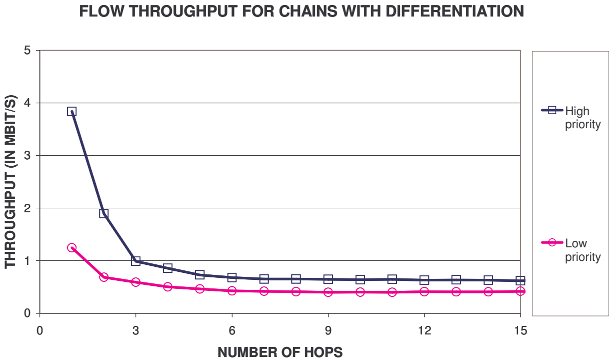

Fig. 3. Flow throughput for chain ad-hoc networks of different lengths with service differentiation.

The second scenario demonstrates the possible benefits of differentiation between nodes to improve the overall performance. The right graph of Fig. 3. illustrates a 4 node ad-hoc network where both node 0 and node 1 initiate persistent flows to node 3. All data packets have to be relayed by node 2 as node 0 and 1 cannot send directly to node 2; nodes 0, 1 and 2 can all sense each other.

Table 1 presents the results without (left) and with (right) differentiation. Without differentiation nodes 0, 1 and 2 obtain the same share of the capacity at the MAC-layer and the throughput are almost the same; node 2 obtains a slightly higher throughput as node 3 is a hidden node for nodes 0 and 1. However, the overall throughput (1.94 Mbit/s) is only as high as the bottleneck node can service and a large part of the traffic of nodes 0 and 1 is lost, wasting valuable capacity. With node-level differentiation more weight is granted to node 2. Al-though nodes 0 and 1 obtain a smaller share, non of their traffic is lost resulting in higher (overall) throughputs.

	Without differentiation			**With** differentiation		
Node	WLAN thr.put	IP thr.put	Packet loss	WLAN thr.put	IP thr.put	Packet loss
	Mbit/s	Mbit/s	%	Mbit/s	Mbit/s	%
0	1.54	0.96	38%	1.26	1.26	0%
1	1.55	0.98	37%	1.27	1.27	0%
2	1.94		0%	2.53		0%
total	5.02	1.94	37%	5.06	2.53	0%

Table 1. Bottleneck scenario without and with node-level differentiation for the bottleneck node 2.

IEEE 802.11 E only provides per-hop differentiation and the resulting end-to-end QoS depends on many variables such as the number of active neighbouring nodes and the number of intermediate hops. Further, differentiating between nodes, which is not possible yet, can also considerably improve the overall performance.

V. NETWORK PERFORMANCE UNDER MOBILITY

In emergency situations, the communication network will be formed by semi-static nodes (vehicles and gateways to the infrastructure) and highly mobile nodes (rescue workers and small mobile equipment). Connectivity between the different nodes will change over time due to the mobility of nodes. Therefore, the effectiveness of the communication between nodes depends heavily on the mobility pattern. As a first-step approach to analyzing the impact of mobility on the performance, we consider a network with multiple fixed nodes and a single mobile node. Data packet transmission is from a fixed node to the mobile node.

A. Model

The network model comprises $M \geq 1$ source nodes and a single mobile sink node. The sink node moves around such that the source nodes alternatively (in a cyclic fashion) may transmit data packets to the source. The visit time of the sink node (and thus the transmission time available per source node) is exponentially distributed with mean $1/\xi$. For the rest, the sink node behaves autonomously. Data packets arrive to the source according to a Poisson process with rate λ. The source nodes are equipped with an infinite queue to store packets. Service times are generally distributed with mean $1/\mu$. We set μ here equal to 1. Packet transmissions may be preempted upon which the transmission will be restarted at a next visit.

B. Analytical approach

Let us consider first the marginal queue-length distribution. To this end, we study a single queue in isolation. The model for a single queue boils down to the unreliable server model (USM) [13]. This is a well-known queuing model for which the distribution of the queue-length (N) is available. The mean queue length, E[N], equals:

$$E[N] = \lambda((M-1)\mu + 2M\xi) / (2\xi(\mu - M\lambda))$$

Next, we analyze the joint queue-length distribution, in a situation with multiple queues. Since the queue lengths are dependent (if one queue is almost empty, the others are likely to be full), this cannot be done with the same approach. Therefore, we model the network as a polling model with an autonomous server for which we obtain the joint queue-length distribution. Our analytical approach builds on the work of Eisenberg [14]. We set-up a system of equations which relates the queue-length distributions at various specific instants. The solution of this system is obtained by the explicit determination of the distribution at visit completion instants via an iterative approach. The latter approach is similar to the approach introduced by Leung for probabilistically-limited polling models [15]. Although our approach is exact, we are not able give explicit closed-form expressions for joint measures. More details on the analytical approach can be found in [16]. Using our analysis, we are able assess the dependence between the queue lengths. As an example for 3 queues (M=3), we depict in Fig. 5., the coefficients of variation for the queue lengths conditional on the server's position as function of ξ. (We use the notation: $\Lambda = M\lambda$).

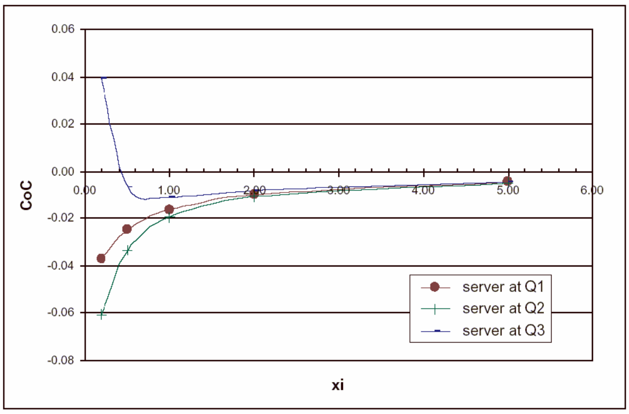

Fig. 5. The coefficient of correlation as function of ξ for Λ=0.15 (exponential service times).

We observe that there exist regimes for which there is hardly any correlation between the queue lengths. Under these regimes, we can successfully apply efficient approximations for the joint queue-length distribution based on the simple analysis of the USM. These approximations are especially valuable for large networks, since the computation time for the exact approach may grow large in these cases.

In future work, we will study other network structures such as a (multihop) chain model or a multi-path model, generalizing to general topologies. We strongly believe that similar techniques as described above may be prove useful to analyze such models.

VI. CONCLUSIONS

In this paper we presented a number of results of the projects Adaptive Ad-hoc Freeband Communications and Easy Wireless, improving the possibilities to build ad-hoc emergency networks supporting quality of service for time-critical services. Conclusions of our work are: (1) with the presented extensions of the OLSR protocol, selection of the best quality route becomes possible; (2) deploying multichannel mesh networks can lead to significant capacity improvements; (3) the analysis of the 802.11E QoS differentiation mechanism shows that in a multihop situation the differentiation of QoS is limited, it would be better to introduce differentiation between the nodes; (4) the performance of an ad-hoc network with mobile nodes can be adequately analysed by using a polling model with an autonomous server.

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