DESIGN CHALLENGES FOR ROBUST GROUND-TO-GROUND WAVEFORMS IN TACTICAL SOFTWARE-DEFINED RADIO AD-HOC NETWORKS

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ABSTRACT

With the advent of software-defined radio devices, mobile ad-hoc networks have gained additional capabilities due to the ease of reconfiguration of the air interface and protocol stack. While work in the area of car-to-car networks and user mobility often focuses on the effectiveness and efficiency of a certain protocol stack, software-defined radio devices offer the possibility of switching between protocols, frequencies and medium access and medium division mechanisms. In this paper, we give a comprehensive literature review and study on design challenges for robust tactical ad-hoc networking waveforms.

1. INTRODUCTION

Software-defined radio (SDR) technology has since its inception in the late 1970s and after coining the term itself in the 1990s [1] now entered the stage where large-scale procurement and subsequent deployment of SDR devices is feasible. Especially in the public safety and military sector, the flexibility of the SDR approach is the basis of the US *Joint Tactical Radio System* (JTRS), its German equivalent *SVFuA* or the Finnish SDR programme [2].

Using the SDR programmes as a key technology and step stone, initiatives for new, wide-band, high data-rate capable digital radio links have started. But while air-to-air data links (e. g. Link 16 [3]) usually operate on the assumption of line-of-sight communication, in the ground-to-ground domain this does not hold and challenging conditions and phenomena have to be surmounted in the design of infrastructureless terrestrial radio communications supporting highly mobile nodes.

The rest of this paper is structured as follows. The current section introduces the concept of a waveform and gives a short overview over MANET peculiarities. Section II gives an exemplary scenario from which we derive a set of challenges in Section III for waveform development. Section IV concludes this paper.

1.1. Waveforms

One of the key terms in the SDR world is the notion of a waveform, which in contrast to the electrical or communications engineering term encompasses not only the *signal in space* but denotes the whole protocol stack from the physical up to the application layer.

While the various national SDR projects focus in the first project phase on emulating existing radio gear through waveforms that implement those legacy radio communication systems, there are also initiatives such as the *Coalition Wideband Networking Waveform* (COALWNW) on their way researching and developing future waveforms capable of IP-networking and having mobile ad-hoc (MANET) characteristics; In the commercial sector, vendors offer proprietary SDR-MANET solutions.

In order to facilitate development, testing, and—up to some degree—portability, waveform development is often based upon the Software Communications Architecture (SCA) [4] which specifies a system architecture for SDR waveforms and platform software.

1.2. MANET peculiarities

While legacy radio systems and digital radio data links are designed around a network model that coincides with the broadcast domain of all nodes (*single hop* behaviour) and usually employs pre-configured, static setups, mobile ad-hoc networks (MANETs) in contrast stress infrastructure-independence, self-configuration, and *multi hop* routing of data packets between nodes. High flexibility does not come for free: Drawbacks include additional overhead due to the need for configuration information distribution, routing, and most prominently the inefficiency incurred by the medium access procedures due to the inherent broadcast nature of the radio medium.

Information-theoretic research into the capacity of wireless networks have been done for example by Gupta and Kumar [5] who derived for the maximum obtainable throughput in the non-interference case $\Theta(W/\sqrt{n \log n})$ bit/s. Furthermore, the maximum obtainable bit rate-distance product for n nodes in an area A is bounded by $\Theta(W/\sqrt{An})$ with W as the node's transmission bit rate. Toumpis and Goldsmith [6] also included multicast traffic in their analysis [7], and Garetto *et al.* [8] have included general node mobility into capacity considerations. In summary, large single-hop networks reduce maximum possible network throughput, which often leads to hierarchical network structures with increased management overhead.

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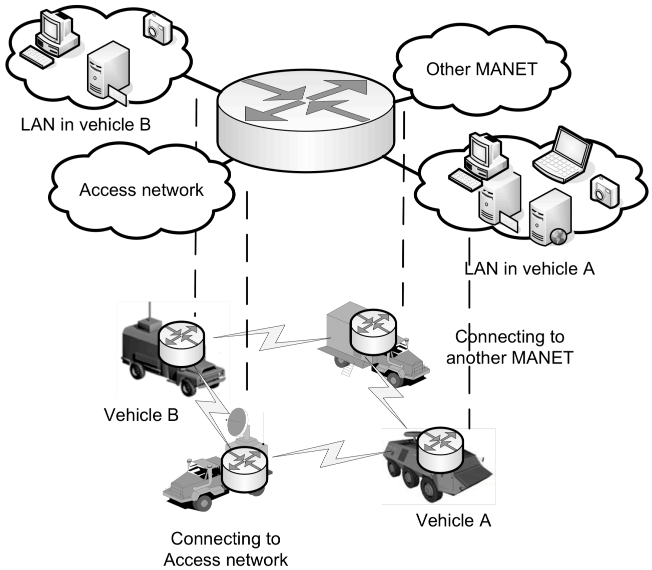

Figure 1: Ground-based tactical MANET acting as communication backbone.

2. TACTICAL SCENARIO

In contrast to the line-of-sight (LOS) and extended LOS (ELOS) dominated air-to-air (A2A) and air-to-ground (A2G)/ground-to-air (G2A) tactical radio networks, ground-to-ground (G2G) radio networks possess inherent difficulties due to their predominantly non-LOS propagation characteristic and channel multipath fading. While the scenario presented in this section has its roots in military crisis-intervention operations, its intrinsic properties are equally present in civilian catastrophe relief, and vehicular networking.

An exemplary ad-hoc radio network for emergency relief or crisis-intervention purposes (as shown in Figure 1) consists of multiple vehicular radio nodes, each possibly containing local subnets. Having either been supplied with multi-line radios or with multiple single-line radios, some of the nodes possess links with adjacent units or provide connectivity to a backbone network via long-haul links. The radios themselves operate in the VHF, UHF and lower SHF frequency bands ranging from a few tens of MHz up to a few GHz.

Spatially the nodes are distributed mostly over an area of a few square kilometres with node distances usually between a few hundred metres up to five kilometres. The topography and morphology spans quite different types: Urban, rural, hilly, or even mountainous terrain, intermittent up to dense vegetation, and building structures in urban environments.

Short-range direct communication relations exist between a node and its adjacent peers; communication with distant nodes is achieved either by routing at the network layer or by using multi-line capabilities (relaying or gateway functionality). Usage of wireless ad-hoc networks as distributed network elements [9] is a rewarding technology to encapsulate the wireless transport network and interconnect communication enclaves into a superstructure.

Communication includes digital voice and video, traffic between command, control, and information (C^2I) systems and terminals, and in the military context fire control (sensor to shooter) communications. Inter-vehicular position and status reports as well as relaying of remote communications are also part of the overall information exchange between nodes.

From data of tactical radio communications in a military context obtained from the German Armed Forces IT Office, it can be deduced that about 85% of all communications take place with peer nodes in less than 5 km distance; 10% of peer nodes are in less than 10 km distance and the last 5% are situated less than 50 km away.

The node topology depends on the specific assignment (e.g. object protection with a central set of nodes, patrols, checkpoints, convoy), mostly a setup consisting of a set of loose clusters can be assumed.

Node mobility at typical vehicular speeds gives relative velocities v_{rel} between nodes with a maximum of 300 km/h and a mean v_{rel} of 80 km/h. Slow-moving airborne nodes such as helicopters are also included in the mobility model.

3. CHALLENGES

From the scenario as described in the previous section, we can derive a number of interesting and challenging topics of ground-to-ground tactical networks.

In this section, we give an overview over the challenges posed by source coding, channel coding, and medium access, as these topics are the most influential ones.

3.1. Source coding

Efficient voice and video codecs are tantamount to good overall performance. Typical voice codecs and their specifics are given in Table 1. For extremely low bit rates, codecs such as G.728 [24] (LD-CELP, Annex H/J) or *Codec 2* (2.5 kBit/s codec output rate) can be used.
Bearing in mind that the data rate as given in Table 1 is the raw codec data rate, the subsequent encapsulation into Real-time Transfer Protocol (RTP, 12 bytes), UDP (8 bytes) and finally IP (IPv4: 20 bytes, IPv6: 40 bytes) gives the real-world data rates (without any MAC or PHY overhead).

In general a compromise between small user data packets, protocol overhead, send delay, and radio channel quality has to be made. Header compression techniques such as *Robust Header Compression* (ROHC) [57] and alternative layer-3 protocols (e.g. STANAG 5066) are a solution approach in that respect.

Table 1. Voice-over-IP specifications for a simplex flow (PPS: packets per second)

Standard	Packet size	Sample duration	Data rate	PPS
G.711	120 Byte	15 ms	64 kBit/s	66
G.729A	10 Byte	10 ms	8 kBit/s	100
G.723.1	24 Byte	30 ms	6.4 kBit/s	33

Table 2. Information exchange QoS requirements

Communication type	Data rate	Delay	Real time
Voice (VoIP, duplex)	≈ 70 kBit/s	150 ms	Soft
Fire control	< 100 kBit/s	< 100 ms	Hard
C^2I	> 50 kBit/s	1 s	No

Table 3. Radio channel setups for a wide-band waveform

Bandwidth	Frequency	Range	Data rate	Subcarrier
25 kHz	225-1000 MHz	> 20 km	16 kBit/s	Single
75 kHz	225-1000 MHz	10-20 km	64 kBit/s	Single
250 kHz	600-3000 MHz	5-12 km	256 kBit/s	Multi
750 kHz	600-3000 MHz	5-10 km	1 MBit/s	Multi
2 MHz	600-3000 MHz	5-8 km	2 MBit/s	Multi
7.5 MHz	600-3000 MHz	0-1 km	10 MBit/s	Multi

Practical video transmission over military narrow-band VHF/UHF radios has been demonstrated recently by Ayres [25]; preliminary practical tests have shown that the combination of sender-side buffers and wavelet compression give good usability due to the wavelet compression's mode of operation: the first transmitted image component is of moderate to bad quality and is progressively improved by subsequent transmission of higher-order corrections.

A case study of air-to-air tactical radio link performance has been conducted by Holland [26]; although the results cannot be used for the G2G case as such, the methodology is sound and work in the G2G area is under way at the moment.

Data rates for the applications voice, fire control and C^2I are given in Table 2; for reasonably good voice quality, about 35 kBit/s per simplex flow with a loss rate under 1% and latency under 150 ms shall be provided [27] and requires soft real-time transmission. Fire control traffic usually requires only a small data rate, but requires hard real-time transmission and a smaller delay than voice or video. C^2I communications at last often is messaging and a typical message mostly has a few kilobytes of data; delays in the order of magnitude of seconds are satisfactory.

3.2. Channel coding

The difficult wave propagation properties of the G2G case combined with highly differing terrain necessitate channel models that are able to support this degree of variability.

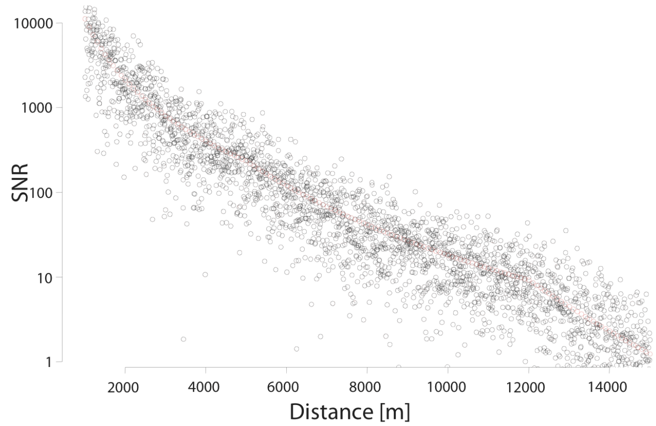

Figure 2: Monte-Carlo simulation of the SNR as function of transmit distance in a Nakagami fading channel ($\lambda = 0.375$, Pt = 50, $\gamma = 2.4$, m = 2).

Standard models include—apart from simple additive white noise Gaussian (AWGN) channels—the Rayleigh [10] (multipath propagation without dominant LOS component), Rician [11] (multipath with dominant LOS component), and Nakagami [12], [13] fading channels. Figure 2 shows a simulation of the SNR depending on the node distance for a Nakagami channel. Assaad *et al.* give an analytical throughput model for 2G/3G HSDPA under Nakagami fading and Alexandropoulos *et al.* [14] provide results for the multivariate Nakagami-m fading model.

Performance of tactical VHF communications has been studied by Berger *et al.* [15]; van Heerden [16], [17] analyses models for VHF frequency-hopped channels. Channel modelling for the 2G mobile communication systems has been conducted as part of the EU COST programme project 207 [18] while Asplund *et al.* [19] discuss the typicality of the urban channel model.

Vehicular radio communications, albeit with a fixed base station, are already modelled and specified in the DAB [20] and T-DMB [21] standards; the PHY-layer performance in fast mobile channels (DVB-T, T-DMB) has been analysed by Poggioni *et al.* [22]. Up to a certain point the DVB [23] standardisation provides also channel models for the given scenario.

A common problem underlying those papers is the validity of the chosen channel model. Asplund *et al.* ask a recurring question: 'How typical is the "Typical Urban" channel model?'—i.e. how valid are the underlying modelling assumptions. Model verification can be either performed by direct simulation of the electromagnetic field or by real measurements with transmitter and receiver vehicles in the desired environment.

In order to mitigate transmission errors as early as possible, interleaving of data, and forward error correction play a critical role. While long interleavers offer better resilience against burst errors, they increase transmission

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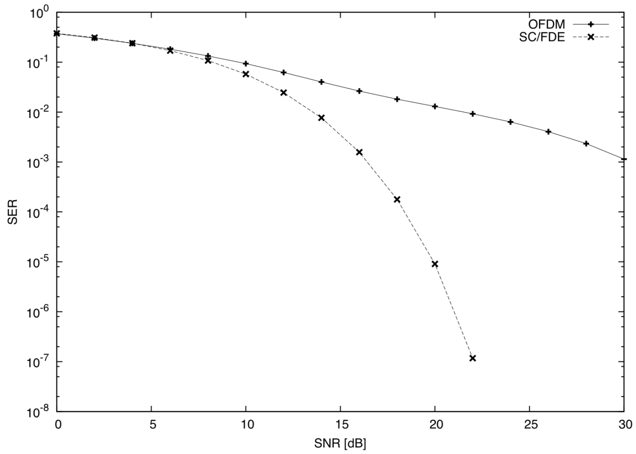

Figure 3: Symbol error-rate simulation for OFDM and SC/FDE using the LTE vehicular A channel model with 512 subcarriers and QPSK subcarrier modulation.

delay due to the fact that the interleaver matrix has to be filled; it depends on the communications profile if and when long or short interleavers should be used.

Forward error correction (FEC) techniques decrease the available net data rate by adding redundancy to the bit stream; the added redundancy enables the receiver to reconstruct the original bit stream from garbled transmissions. Typically used FEC methods are convolution codes, Reed-Solomon codes, or turbo codes [28]. Jordan and Merheb [29] give an analysis of turbo-coded UHF SATCOM performance. Their results show that turbo-coded transmissions can be successfully employed on operational satellite systems and performance is superior to available convolutional codes.

Single-carrier FDMA (SC/FDMA), as specified in the 3GPP's long-term evolution (LTE) system, shows promising results over OFDM(A) by virtue of smaller symbol error-rate (SER) under the same SNR conditions and a much better peak-to-average power ratio (PAPR). The lower PAPR poses a much lighter constraint on the linearity of the amplifier and enables more cost-efficient mobile transceivers. Figure 3 shows simulation results for the symbol error-rates of OFDM and SC/FDE and Figure 4 shows a comparison between the simulated PAPR probability distribution functions of OFDMA and SC/FDMA.

Table 3 gives an overview over possible channel setups for wide-band networking waveforms. Channel bandwidths of 25 kHz or 75 kHz, albeit not wide-band, are necessary for a usable specification of such a waveform in order to make use of existing frequency regulations and channel assignments.

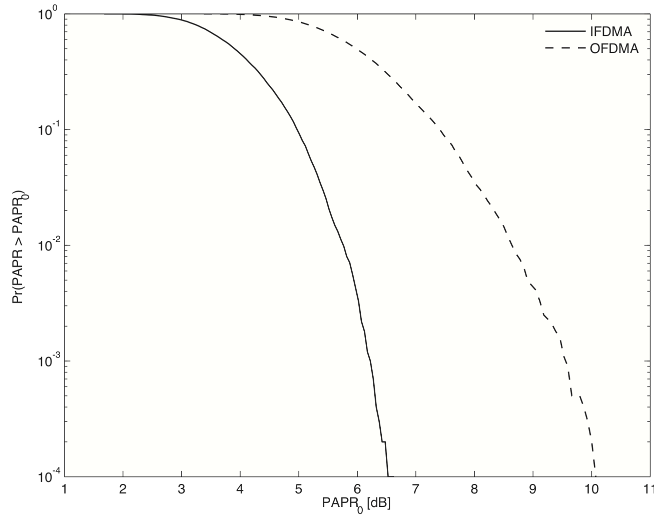

Figure 4: Comparison of the peak-to-average power ratio (PAPR) complementary cumulative distribution function (CCDF) for SC/FDMA (IFDMA) and OFDMA. Simulation performed with 512 subcarriers, 128 input symbols, IFDMA spreading factor 4, QPSK modulation, and roll-off factor 0.22.

3.3. Medium access

While the sections above had end-to-end or node-to-node performance as core areas, in a shared medium such as a radio channel medium access (MAC) technologies and protocols play a key role. Several aspects have to be considered: prioritisation and break-in capabilities, quality of service (QoS) support, channel usage efficiency, and fairness.

3.3.1. Non-deterministic medium access

Starting with the Aloha protocol, a class of carrier-sensing protocols has been developed. The most ubiquitously employed protocol is based on the CSMA/CA technology as present in the IEEE 802.11 [31] standard.

In contrast to wireless LANs, tactical networks usually require guaranteed access, prioritisation and hard QoS. The inherent probabilistic nature of the non-deterministic MAC protocols makes it hard or impossible to guarantee such parameters.

3.3.2. Deterministic medium access

Deterministic MAC methods divide a space spanned by a number of dimensions such as frequency, time, or code, into fixed subspaces (time slots, sub-channels, etc.) and assign each station a predetermined or self-organised number of subspaces for transmission.

The deterministic assignment of transmission subspaces makes it possible that each station is able to give upper and lower bounds for channel access time and the size of its transmission budget.

Albeit a very interesting and efficient method in base station-centric setups, code-division multiplexing (CDMA) has severe drawbacks due to the necessity of received-power regulation. Abdulalli and Rouvaen [30] have studied CDMA in MANETs under varying node topology and give preliminary MATLAB simulation results.

Time-division medium access methods are a successfully employed class of MAC methods due to their comparatively easy deployment and usage. Stevens *et al*. [32] have presented the results of a scenario-based analysis of TDMA methods in the military context, but they limit themselves to very favourable transmission conditions (flat terrain).

An interesting class of self-organising TDMA protocols has been developed following the initial presentation by Lans [33]; these protocols are successfully employed in the aviation domain as the basis for the VHF Digital Link Mode 4 of the ICAO and in the maritime domain as the basis of the AIS as standardised by the IMO.

A number of studies have been undertaken in the context of such self-organising TDMA algorithms; Dhamdhere and Gronkvist [34] surveyed the effects of joint node and link assignments in such networks, further work by Gronkvist *et al*. [35], [36] focuses on distributed scheduling and throughput performance

STDMA throughput under different bit error rates and in maritime networks has been analysed by Wu *et al*. [37], [38] while modifications of the STDMA protocol employing variable power and rate control have been analysed by Somarriba [39], who has also investigated the influence of slow mobility [40].

The Unifying Slot Allocation Protocol (USAP) as developed by Young [41]–[43] mitigates some of the drawbacks of time-division methods and is successfully employed as the basis in a number of vendor's ad-hoc networking products.

Cross-layer design of routing and medium access (AODV and Spatial-TDMA) as undertaken by Shang *et al.* [44] as well as Xida and Qiguo [45] is an interesting and effective approach towards maximising the overall efficiency of an ad-hoc networking system.

Albeit CDMA methods are not ideally suited for MANETs, Bank has contributed an interesting approach by combining OFDM and CDMA multiplexing [46].

Interleave-division multiple access (IDMA) as developed by Ma and Ping [47] and Ping [48] is an interesting approach for deterministic medium access. Work done by Hoeher *et al.* [49], [50] further elaborate the theoretical foundation of this method and describe the design of such interleavers [51].

4. CONCLUSION

Infrastructureless vehicular ad-hoc networks with deterministic behaviour will be an integral part of future communications in the military as well as the civilian sector.

While a large body of work already is in existence tackling separate aspects of such networks, the most challenging aspect is the integration of these concepts, methods, and protocols into a deployable product.

Good channel models for the notoriously diverse and adverse ground-to-ground radio propagation, especially for a larger number of differing terrains, are currently as needed as the design for QoS-integrated medium access protocols.

Management security aspects such as described by Hanigk [52] are necessary to achieve a secure yet easily deployable network infrastructure.

Future work such as the development of medium access protocols, e.g. eMAC [53], and the study by Bilstrup *et al.* [54] of standardised protocols such as 802.11p in vehicular networks show a possible way ahead.

Albeit being a former buzzword, cross-layer design approaches, especially in the physical and medium-access domain and the integration of multiple aerials as described by Spyropoulos and Zeidler [55] show very promising results. Cross-layer quality-of-service (QoS) design as already under evaluation by Lin *et al.* [56] is therefore the next stepping-stone towards maximised efficiency.

As a concluding remark, we see the development of software-defined radio platforms as a truly transforming technology and enabler for efficient ground-to-ground waveforms. A lot of building blocks are already in place and it is now our task to tackle the challenging aspects present.

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