Chaotic Ad-hoc Data Network – A Bike Based System for City Networks

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***Abstract*—Cities are facing an increasing number of bicycles being used by urban citizen and the need of monitoring and managing this type of traffic becomes part of municipality and city administration. Bicycles shall be able to communicate between each other, exchange data with information service providers in the city and broadcast alarm and emergency messages. In this work we describe a wireless sensor network infrastructure approach designed especially for data messaging for bicycles, being independent of existing networks of telecommunication operators. The proposed communication network is assumed to be a decentralized, chaotic ad-hoc network established by a transceiver mounted on each bicycle. With this approach important information from bicycles moving around in the city can be gathered without depending on 3rd party network infrastructures. This network can build the basis for further applications for bicycles like optimized traffic management.**

Keywords*—Radio transceivers, ad-hoc networks, asynchronous transfer mode, bicycles, wireless sensor networks

I. Introduction

Telecommunication for wireless sensor networks and similar applications with small data amounts to be transmitted in packets is lacking an infrastructure specifically designed for this purpose. The heavy investments of mobile operators worldwide in network technology are targeting video, voice and multimedia services and are not designed for simple packet radio transmission. This opens an opportunity to design a data communication network fitting exactly the needs of bicycles and consider affordability and the dynamic nature of moving bicycles.

Bicycles will be equipped with small sized data transceivers for capturing telemetry data and transmitting the information in form of packets to other bicycles in the neighbourhood. The packets with the information will travel from one bicycle to the other till it reaches a receiver for processing the information. The advantage of such an ad-hoc network is the absence of any dedicated and static network nodes, making it cost effective, and robust. The more bicycles are in a certain area the amount of data to be communicated is rising, but in the same moment the capacity of the network increases with each bicycle added.

Using the existing infrastructure of telecommunication operators to transport data packets of small size but in huge amounts has a major constrain in costs. Operators need to finance the heavy investment in their network, which drives the price they have to charge for a simple data packet transport service. Initiatives all over the world start projects for a “BikeNet” based on mobile operators infrastructure with GSM or GPRS subscriber modules for the bicycles failed due to the high charges for operating the network.

The second limitation for using the infrastructure of telecommunication operators is overhead produced by the subscriber management, which they have to do for each client connecting to their network. Each bicycle would be administrated and managed like a mobile phone or smartphone client, which makes the operation of such an infrastructure very ineffective. The transceiver hardware at the bicycle would need to be equipped with a SIM card, which again drives costs of the hardware as well as operational overhead.

Other existing infrastructure like Wireless Local Area Networks (WLANs) in cities are available in public areas, but lack continuous coverage. Chang et al. is discussing in [1] a network infrastructure which assumes the existence of network nodes on public places with a high frequency of passing bicycles. This concept of an ad-hoc network requires network nodes or stations all over the coverage area and will have bicycles being out of reception between the cells of stations.

The presented approach is based on a chaotic ad-hoc network which will be build using specifically designed hardware for bicycles. Each equipped bicycles builds a node in the ad-hoc network. The network infrastructure will be operated in frequency bands assigned by ITU or local authorities. We assume that we can not predict which bicycles are participating and forming the network at any point in time and the topology of the network infrastructure is changing randomly. Packets route for travelling through the network is depending on the initial topology at the time of transmission and a matter of continuous change till it reaches its destination. The topology of the network infrastructure is a chaotic system formed by randomly appearing and moving network nodes. Amin compares performance of topologies with fixed and mobile network nodes in [2].

The remainder of this paper is structured as follows: related work is covered in Section II. In Section III the population of bicycles in cities and countrysides is analyzed to understand the coverage requirements for an ad-hoc network. Section IV explores the transmission capability of a network without nodes and the requirements for packet routing. In Section V the selection of the frequency band for operation of the network will be discussed as well as the impacts on coverage and transmission rate. The paper finishes with a conclusion and ideas for further work in Section VI.

II. Related Work

Packet radio based data communication started to being used by radio amateurs to establish the Automated Position Radio System (APRS) Network, a network to transport location information and telemetry data in the 1980s. A much wider application of packet radio are today the General Packet Radio Service (GPRS) communication services of the mobile telephone networks and Terrestrial Trunked Radio (TETRA) communication system used by public authorities. All are structured networks with pre-defined topologies and a network authority monitoring and controlling communication.

Nakamura et al. describes in [3] a field test in Tokyo involving bicycles with sensors communication in a Wide Area Ubiquitous Network (WAUN). The idea of WAUN is based on a network design specifically for sensor or telemetry networks, but in contrast to the concept presented in this paper, WAUN is based on a cell structure with network nodes operating at 280 MHz and covering an area of 5 km radius [4]. The limitation of the WAUN concept is the offered transmission rate up to 9.6 kbps and the fact that one transmission blocks the communication channel for the entire area of 5 km radius.

The Copenhagen Weel project [5] implements a device on each bicycle with sensors as a Global Positioning System (GPS) receiver or kinetic sensors. The devices are connected via Bluetooth to a smartphone of the cyclist. The communication infrastructure in this project is entirely based on the existing mobile phone operators network. It requires the cyclist to carry his smartphone while cycling and have a data subscription with a local operator.

Also Eisenman et al. introduces a bikenet in [6] which is leveraging the cellular data channel of the cyclist's mobile phone to transmit data captured with sensors at the bicycle.

All concepts so far have in common, that they are designed with a hierarchical, fixed planned node structure and not using the idea of ad-hoc networking without dedicated nodes forming a backbone. A lot of initiatives have focused on using mobile networks of telecommunication operators as a network infrastructure struggling with the costs for deployment and operation.

III. Concept for a Wireless Sensor Network Based on Bicycles Equipped With Transmitters

Bicycles are equipped with a small sized transceiver as shown in Figure 1 with sensors to capture kinetic and location information and transmit them based on events into the ad-hoc network. The transceiver is powered by a rechargeable battery and the bicycle dynamo or if an e-bike, the transceivers battery is charged from the bicycle power system. The transceiver integrates a GPS receiver to log the bicycles location and altitude. Kinetic sensors are not only reporting the speed, but also raise alarms when there are heavy shake ups caused by a crash.

The system is designed for tracking each bicycles location, speed, altitude, shock and noise levels to offer a public information service by the city administration. This would allow to raise automatic alarm messages when a bicycle is crashed or involved in an accident, but also to find lost or stolen bicycles. For sportive citizen the infrastructure would allow to monitor the daily performance of their rides and much more. Instead of using a central infrastructure the bikes directly build a communication network to transmit this information.

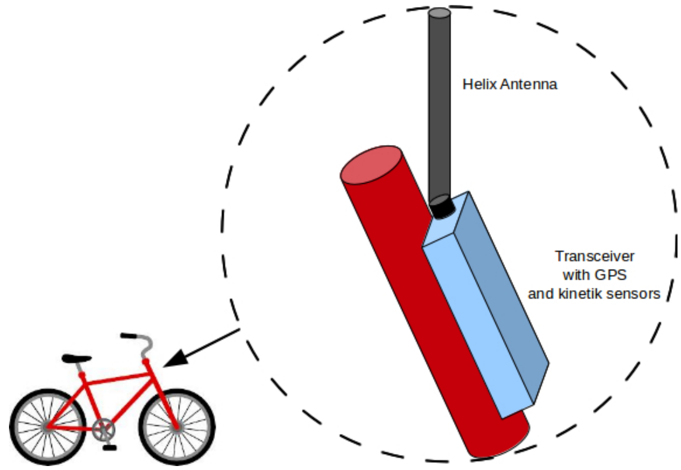

Fig. 1. Transceiver mounted at the bicycle

A single transmission at 5 Watt HF power will require 7 to 8 Watts at 5 Volt from the supply for the transmitting timeslot. In receiving mode the hardware will consume about 0.1 Watt and in stand-by mode consumption will be down to 0.01 Watt. As a bicycle transceiver will be equipped with a small battery of 500 mAH up to 1000 mAH multiple recharging is required in one day usage.

A. Bicycle Distribution in Cities

Looking at recent statistical data of the number of bicycles in cities shown in Figure 2 proofs the fact that there are enough bicycles available and used to establish an ad-hoc network. European cities like Berlin or London have counted about 600 bicycles for each 1000 citizen. Shanghai and Beijing are counting higher numbers, about 700 bicycles for each 1000 citizen, but have a much higher use rate. For the concept in this paper it is important to look at the number of active bicycles, being used at the same time.

The city of Vienna is taken as an example in this paper and the figures used for the population and usage of bicycles are based on the recent publication of Federal Ministry for Transport, Innovation and Technology, in Austria [7]. In the city of Vienna are about 1,250,000 bicycles and 11.1% are used as main means of transport, which allows the assumption that we have about 138,000 bicycles being used at each moment while daytime in the city with an area of 414 km^2. In the country of lower Austria with an area of 19,186 km^2 the study talks about 1,200,000 bicycles, whereof we can assume, that 130,000 are in use at each moment. The usage of bicycles is depending on the season and the weather, in night times it might go done to nearly zero.

City / Region	typ of area	area [km²]	# of bicycles	# of bicycles in use	concentration [bicycle / km²]
Berlin	city	892	2,534,444	281,323	315
Beijing	city	16,808	12,414,000	2,482,800	148
Shanghai	city	6,341	13,811,489	2,762,298	436
Toronto	city	630	1,830,542	203,190	322
Boston* * land area	city	125	432,316	47,987	383
London	city	1,572	5,885,208	653,258	416
Vienna	city	415	1,246,490	138,360	334
County of Lower Austria	countryside	19,186	1,200,000	133,200	7

Fig. 2. Bicycle concentration in cities worldwide based on [7]

B. Coverage of a Bicycle Based Ad-hoc Network

The transceiver hardware will allow transmission over a distance of 2 km in urban areas and about 3.5 km in the countryside. Each bicycle transceiver will cover therefore a cell with the radius of 2 to 3.5 km. All assumptions about Radio Frequency (RF) link distances in this paper are based on field tests of the authors in urban and countryside areas. This is depending significantly on the choice of frequency for operation of the transceiver and the antenna which will be discussed in Section V.

	typ of area	area [km²]	transmission distance [km]	area covered [km²]	min.# of bicycles
Vienna	city	415	2	13	33
County of Lower Austria	countryside	19,186	4	38	499

Fig. 3. Example of required bicycles participating in the ad-hoc network for Vienna

To understand the scalability and visibility of an ad-hoc network without nodes we look into the minimum amount of bicycles which are needed to participate in the network all the time. As presented in Figure 3 in the city of Vienna a minimum amount of 33 active bicycles spread equally over the area are required to achieve full coverage. With the average amount of 120,000 active bicycles in this area the scenario in terms of coverage for the transmission of data packets seems realistic.

IV. Robust Transmission in the Decentralized Ad-hoc Network

Information in form of data packets can be received by the bicycle and will be transmitted by the bicycle for other receivers. Transmitting and receiving of data packets for short messaging and status information like location, speed, etc. will consume only small timeslots and leave the transceiver of each bicycle available to serve as a relay for other data packets. When not transmitting or receiving data packets addressed to itself the bicycle will receive any packet and re-transmit the packet. A data packet can travel across the area hoping from bicycle to bicycle.

The AX.25 link access protocol [8] transports data using virtual circuits to guarantee that the information is transferred completely and in the right order between sender and receiver. The sender selects for each transmission packet a receiver as well as the path the packet should travel.

This allows the design of an ad-hoc network without authorities involved and is the base for a decentralized network without dedicated network nodes. The virtual circuits are build with I-Frames, which transport the actual information and Supervisory-Frames, which confirm the I-Frames and may request a re-transmit. In the ideal case of transmission without any interference the transport protocol allows the sender to send 7 I-Frames of 256 byte in a row. After this the receiver has to confirm with short Frame called the RR-Frame.

```
TX: 1st I-Frame 256 byte information
TX: 2nd I-Frame 256 byte information
TX: 3rd I-Frame 256 byte information
TX: 4th I-Frame 256 byte information
TX: 5th I-Frame 256 byte information
TX: 6th I-Frame 256 byte information
TX: 7th I-Frame 256 byte information
RX: RR-Frame for I-Frame 1 to 7

...

TX: 8th I-Frame 256 byte information
TX: 9th I-Frame 256 byte information
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TABLE I. FRAME BASED NETWORK COMMUNICATION

A. Bandwidth for the Bicycle Based Ad-hoc Network

Within one transmission the total amount of information is $7 \cdot 256 = 1,792$ bytes. Considering 8 bit / byte the bit amount is 14,336 bit. This transmission has a cost of 8 frames and needs to switch on and off the transmitters.

Flag	Address	Control	PID	Info	FCS	Flag
01111110	112/224 Bits	8/16 Bits	8 Bits	256 * 8 Bits	16 Bits	01111110

Fig. 4. AX.25 frame and structure of a data packet

Figure 4 shows details about the frame and structure of a data packet. Each AX.25 packet includes header, receiver (including SSID) and path information and a protocol identifier information summing up to an amount between 15 to 71 byte depending how complex the path information is. For 8 frames (7 I-Frames and 1 RR-Frame) we will need to add in the worst case $8 \cdot 71 = 568$ bytes or 4,544 bits, which we have to add to our 14,336 bits of information. The AX.25 Protocol uses the HDLC-Format (High Level synchronous Data Link Communication) for checksum and frame structuring. This adds another 16 bits for each frame, in this case $8 \cdot 16 = 128$ bits and another 80 bits for block-limiters summing up to 208 bits. The frames are stuffed with “0” before being transmitted, to avoid start and end flags of the frame within the packet. This leads to additional 1.5% bits. To transmit net information of 14,336 bits (or 1,792 bytes) we need to send 19,374 bits (or 2,422 bytes). At a rate of 9.6 kbit/s the time to transmit this information is about two seconds. This assumption allows 1792 bytes for the net information of the transaction and is based on 9.6 kbit/s on the VHF channel. In a simplex channel mode each bicycle transceiver will be able to handle 30 transmissions each with seven information packets and one supervisory packet per minute. At a transmission rate of 115 kbit/s the transmission would take 170 milliseconds and allowing 350 transmissions per minute.

Assuming a transmission rate of 9.6 kbit/s a bicycle may transmit or receive a maximum of 10 transmissions per minute addressed to or from them, which leaves time for a minimum of 20 other transmissions to be relayed by the bicycle transceiver. The calculation with 20 transmission to be relayed each minute is a worst case with such a bad signal-to-noise ratio that the transmission rate goes down to 9.6 kbit/s.

B. Addressing

To explore how packets will travel in the ad-hoc network without dedicated nodes and without a central authority setting rules and controlling the connections, we need to look into the address part of the frames. An AX.25 packet structure for the approach looks as shown in Figure 5.

	Flag	Dest. Address	Source Address	Path Entry	Control Field	Protocol ID	Info Field	FCS	Flag
Bytes (8 Bits)	1	7	7	0 – 56	1	1	1 – 256	2	1

Fig. 5. AX.25 frame structure for the approach

The flag field at each end of the frame is the bit sequence 0x7e that separates each frame. The first 7 bytes (each 8 bits) after the flag hold the destination address, which could be the unique identifier for the bicycle being the receiver. The following 7 bytes (each 8 bits) are for the source, the senders address. This could be either another bicycle or any destination which is part of the network and should receive the information. Following the destination address are 0 to 56 bits holding the path information. With maximum 7 bytes the sender can define how the packet will travel through the network using other bicycles as repeaters. The control field and the protocol ID are used for enhanced applications, which are not discussed in this paper. The information field can be up to $7 \cdot 256$ bits long and holds the message or data to be transmitted. Finally the Frame Check Sequence (FCS) field holds the checksum to ensure the integrity of the received packet.

C. Packet Forwarding

This capability of the AX.25 protocol allows the implementation of generic digipeating for the network. The power of such an implementation in the field derives from the idea that packets are propagated without a priori knowledge of the network. The path entry after the destination address will include predefined keywords, which each bicycle transceiver is able to understand when relaying transmission. We look here at three possible parameters in the path entry to explore into the possibilities of generic digipeating:

- RELAY: if the packet is received and the destination address does not match for the bicycles the transceiver will simply digipeat the packets at any time.
- WIDEn-N: the bicycle transceiver receiving a packet with a WIDEn-N entry will digipeat such a packet that is “new” and will subtract 1 from N until N reaches 0. The transceiver keeps a copy or a checksum of the packet and will not digipeat that packet again within a certain time period. This considerably reduces the number of superfluous digipeats in areas with many bicycles in radio range of each other.
- BROADCAST: if the packet is received and the destination address does not match the bicycles transceiver it will simply digipeat the packet for one time.

If the packet received contains a destination address, which does not match the bicycles address, the transceiver will relay - digipeat the packet. The path entry contains parameters set by the sender about the packet flow within the ad-hoc network. This allows more than one transceiver to digipeat on the same RF channel. The last octet of the source address has its address extension bit set to “0”, indicating that more address-field data follows. The path entry is encoded in the same manner as the destination and source address subfields, except for “N” in a “WIDEn-N” entry. The “N” indicates whether a frame has been repeated before already or not. The “N” byte is set to the number of maximum digipeats by the sender, and the bicycle transceiver repeating the packet reduces the ”N” by 1 before it re-transmits the frame. The link-layer AX.25 protocol allows operation through more than one repeater. As a packet progresses through a chain of bicycle transceivers, each successive transceiver, which relays the packet, will modify the path entry, indicating that the frame has been successfully repeated through it. No other changes to the frame are made (except for the necessary recalculation of the FCS). The destination station can determine the route the frame took to reach it by examining the address field and use this path to return frames. Path entries like RELAY have to be used with care, as they indicate digipeating without limiting how far the packet should travel.

The protocol implements further more techniques for packet handling without the need for routing algorithm to define the path of a packet upfront. Hu L. discusses efficiency and purpose of this method in [9].

A central service unit of the city administration equipped with a similar transceiver as the bicycles would receive packets addressed to it from any bicycles. Location data or telemetry data can be collected by a receiver station and reported to a database or web service. Bicycles receiving packets for a central service unit will simply re-transmit – digipeat the packet and finally a service unit will receive the packet and process it. This could include alert messages even rising an action by the city administration.

Assuming the network is only operated on one specific frequency and channel multiplexing is not possible all information has to be transmitted on the same RF channel. The protocol suggested above is able to handle collisions, and is limited to a total amount of 240 transmissions per minute on the RF channel. Each bicycle will cover a cell depending on its RF output power and block the channel for time of transmission.

Before transmitting a packet the sender is listening in to the channel and waits with the transmission till the frequency is free for a defined time. This parameter reduces the probability of collisions, but reduces the overall throughput on the network. The protocol used for the ad-hoc network is based on the AX.25 Link Layer protocol and handles collisions with a supervisory frame following after 7 information frames. The supervisory frame will request a re-transmit of the information in case of corrupted data. The receiver is able to discover corrupted data with the FCS of each packet and trigger the re-transmit with a supervisory frame. The collision handling follows the ITU recommendation outlined in [8] and [10].

In an urban area, like Vienna we might have a concentration of 300 or more active bicycles within 1 km^2. A bicycle transceiver will block the RF channel while transmitting within a radius of 2 km around his locations, an area of 13 km^2. We can expect about 4,200 bicycles in a city to be in the same area, who want to use the same RF channel. So each bicycle would get a free slot every 10 minutes in worst-case scenarios with only one single RF channel. When limiting the length of information for each transmission to 256 Bytes, each transmission will only take one packet, and we will have about 1,500 transmissions per minute on the RF channel. This would allow each bicycle to transmit every 1.6 minutes.

V. Technical Design of the Approach

Several parameters have to be considered for selection of the frequency band, with very different backgrounds as which technology is available at certain costs, the legal environment for getting a license to operate, as well as the propagation criterias at the selected frequency:

- Transmission distance with battery power
- Direct wave propagation in urban areas
- Integration, size, cost of transceiver
- Dimension of the antenna
- Transmission rate, bandwidth
- International available, free frequency band
- Concentration of active bicycles

The most non technical criteria, the legal requirement for a license or permission to operate transceivers at a certain frequency is a critical criteria for the design of a solution. The International Telecommunication Union (ITU) has already named certain frequency bands for ISM and telemetry data and most certainly permission to operate can be acquired for the 2 m or 70 cm band, frequencies between 120 and 180 MHz or 420 to 460 MHz. Propagation at 1 GHz or higher is of too short distance at the available output power with a battery powered transceiver. Frequencies below 100 MHz have wavelength which lead to large antennas and very sizeable transceiver parts which are not usable for bicycles.

To guarantee a transmission rate of 9.6 kbit/s the required bandwidth according to the Shannon-Hartley Theorem [11] is

$$B = \frac{C}{\log_2(1+SNR)}$$

$$B = \frac{9.6 \cdot 10^3}{\log_2(1+10^{20/10})} = 1.44kHz$$

This would allow to operate the network at frequencies below 100 MHz, but because of the criteria to have a transceiver hardware which fits comfortably one bicycle we will need to look at higher frequencies. The channel grid for this band is typically 12.5 kHz which would allow higher transmission rates up to:

$$C = B \cdot \log_2(1+SNR)$$

$$C = 12.5 \cdot 10^3 \cdot log_2(1+10^{20/10}) = 83kbit/s$$

As we could see in Section III, the coverage area of each bicycle transceiver also defines the area where the RF channel is blocked by the transmitting bicycle and no other transmission is possible at the same time in this area in the same RF channel. By operating at a higher frequency than in our example in Section III we would have much shorter link ranges at the same power. Assuming operation in the 70 cm wavelength band, e.g., 430 MHz, would reduce the radius for transmission of one single bicycle transceiver down to 200 to 500 meter in urban areas and up to 2 km in the countryside. This would need a higher concentration of active bicycles to achieve coverage, but allow a much higher throughput on the network.

comparison of	2m Band	70cm Band
ITU ISM Band Frequency	170 MHz	430 MHz
typical link distance	at 5W PA and min. SNR 20dB	
urban area [km]	2.0	0.3
countryside [km]	3.5	1.5
cell coverage area	radius around bicycle location	
urban area [km²]	12.6	0.3
countryside [km²]	38.5	7.1
concentration of bicycles	no of bicycles in coverage cell	
urban area	4,197	94
countryside	266	49
typical transmission rate [bit/s]	9,600	115,000
no of transmissions* per minute *7 data packets	30	350
no of packets* per minute *data limited to 256 bytes	180	2,100

Fig. 6. A comparison of operation in the 2 m band vs. 70 cm band

Figure 6 shows a comparison of the operation on the 2 m band vs. 70 cm band. In urban areas there is clear advantage for the 70 cm Band, allowing smaller cells because of the high concentrations of bicycles. The ad-hoc network is offering a total of 350 transmission with $7 \cdot 256 = 1,792$ bytes of data each minute for typically 100 bicycles in such an area. This allows each bicycle transceiver to send or receive one transmission for itself and relay minimum two other within one minute. Considering that such an ad-hoc network is established without any operator nodes or stations the network offers two free slots per minute for other data to be relayed beside the transmission of the bicycle related data.

Above calculation are based on a single RF channel to operate the network, implementation of a frequency multiplexing over several RF channels can improve the throughput of the network.

VI. Conclusion and Further Work

The power supply of the transceiver at the bicycle needs further research and engineering work. Possible solution to be explored could be a rechargeable battery which is charged permanently while cycling by dynamo. Another possibility would be to have the transceiver as plug able device on the bicycle and the driver has to remove it for recharging at any standard USB port. In any case the battery selection and the recharging method will need to be treated with care as they are critical for the usability. A new implementation of the link layer protocol, which makes use of the availability of 32 and 64 bit CPUs, will increase performance and reliability of the network and the packet handling.

Design of the Antenna is a critical topic for the distance and the quality of the RF links between bicycles. The best antenna shape and dimensions to maximize signal gain are by default too big and will not be accepted by the users. An integrated antenna design similar to mobile phone needs to be explored and tested. Developing such Antennas for the 2m or 70cm band is a time-consuming exercise and required a lot of field testing.

The BikeNet will need interconnection to an existing network like the internet, and service providers for the BikeNet will need to be able to connect to the BikeNet. Interconnection nodes will have a similar design as the bicycle transceiver, but also offer and Ethernet interface. Packets will need to be routed outside the BikeNet so that the information provided by the bicycles can be used.

The implementation of a network based on transceivers mounted on bicycles and operation without central network nodes has a significant cost advantage over a concept involving existing phone operators. The bandwidth required for a network based on bicycles would be a 1 to 2 MHz spectrum in an ISM band allowing 10 or more channels to implement frequency multiplexing capabilities.

The minimum amount of active bicycles in a certain area has to be met, otherwise bicycles are isolated and can not make a RF link to the next bicycle. This would generate areas with no network coverage. Countryside areas may suffer from such situation, especially when frequency in the 70 cm Band or higher will be used.

A major limitation is the need to power the transceiver hardware while cycling. This will require further engineering and investments to develop user-friendly and practicable ways to have the battery fully charged for the transceiver.

The presented approach is based on a single RF channel to operate the network, implementation of a frequency multiplexing over several RF channels is part of further work to improve the network.

The ad-hoc network formed by the bicycle transceivers works without dedicated network nodes and the bicycles transceivers are establishing a transport network for data packets. With each new bicycles added to the network an additional inherent node is added and the size of the network increases. Each bicycle contributes with its own transceiver to the formation of the transport network with part of the transceivers functionality taking over tasks of a network node. Further work has to define ways to compare cost of such an ad-hoc network with the traditional approach to use existing mobile operators networks for transport of data packets.

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