A Glimpse at Bicycle-to-Bicycle Link Performance in the 2.4GHz ISM Band

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***Abstract*—Bicycle-to-bicycle (Bi2Bi) communication can be implemented by well-established technologies in the 2.4GHz ISM band: IEEE 802.11, Bluetooth or IEEE 802.15.4. These technologies have distinct performance due to different physical and data link layers. In this paper, we characterize the mentioned 2.4 GHz-operating technologies over opportunistic links established between bicycles using commodity hardware. We find that, in Bi2Bi links, Bluetooth, IEEE 802.11 at 24 Mbit/s, and IEEE 802.11 with automatic rate adaptation can communicate only in the immediate surroundings (under 15m of range), to maxima of 1.5 Mbit/s, 17 Mbit/s and 25 Mbit/s, respectively. IEEE 802.15.4 and IEEE 802.11 at 1 Mbit/s sustain connectivity up to 30 and 40 meters and peak transfer rates of 50 kbit/s and 800 kbit/s respectively. In addition, we observed that, in all measurement scenarios, link performance depended strongly on whether bicycles were approaching or moving away, rather than on whether one was at the front or back of the other.**

I. Introduction

Bicycles are a widely used commute solution [1]. Bicycle-to-bicycle (Bi2Bi) and bicycle-to-infrastructure networking may support safety and infotainment applications, thus safeguarding cyclists and other road users and improving their mobility experience. Existing V2V technology was tailored for high relative speeds and is power-intensive, partly due to its higher transmit power [2]. In this paper, we evaluate opportunistic connectivity between bicycles supported by less power-intensive wireless technologies operating in the 2.4GHz ISM band, and assess the performance of commodity hardware in Bi2Bi communication. In this band, the most prominent wireless technologies are IEEE 802.11b/g/n [3], Bluetooth [4] Class 2, and IEEE 802.15.4 [5]. Our contributions are the following:

- Experimental characterization of the link performance between transceivers mounted on bicycles in motion, for five different technology setups;
- Identification of whether bicycles are approaching or moving away as the main factor impacting link performance;
- Discussion on the potential applications that each technology can support and on the limitations and challenges of this work.

To the best of our knowledge, no related work provides such characterization of Bi2Bi links.

The remainder of this article is as follows. Section II reviews the literature on bicycle-to-X communication. Section III discusses the experimental hardware and parameter configurations. The experimental characterization of Bi2Bi throughput and range are presented in Section IV. In Section V, we discuss the challenges of Bi2Bi links and the applications each technology could support. Conclusions are drawn in Section VI.

II. Related Work

Communication between two-wheeled vehicles has been explored in the literature. From an application perspective, the use of smart phones and WiFi to identify scooters that run through red lights is presented in [6]. The authors of [7] evaluate the best location to place an IEEE 802.15.4 transceiver in scooters in the particular scenario of communication with a vehicle in the rear, having concluded that the left mirror is the best location. On a network level, an experimental evaluation of IPv6 in the Tour de France is presented in [8]. The *de facto* standard for vehicular communication, IEEE 802.11p, has also been applied to two-wheeled vehicles (primarily scooters). In [9], a transceiver is installed in a scooter and car to showcase safety applications. In [10], the authors evaluate the use of IEEE 802.11p for corner communication, for different types of obstructions (e.g. building, windowed buildings and vegetation).

The link performance of the various technologies has been evaluated in numerous works. Throughput and packet loss measurements of IEEE 802.15.4 in car-to-infrastructure links are reported in [11]. The performance of IEEE 802.11b/g in vehicular communications was evaluated in previous works, such as [12], before IEEE 802.11p became the predominant technology, and more recent studies characterize its performance in infrastructure-to-car links [13]. The work in [14] proposes a negative exponential model to describe packet delivery ratio in IEEE 802.11g links between multi-rotor UAVs. The authors also show that such model is a better fit than the common logistic sigmoid model.

Our work innovates by studying wireless links between bicycles, whereas most vehicle-to-vehicle studies focus on cars and scooters. In cars, antennas can be placed on the rooftop and feature unobstructed isotropic communication; in scooters, there is more metal surfaces and electromagnetic noise and the frame is shaped differently (as the rider does not need to pedal). Thus,

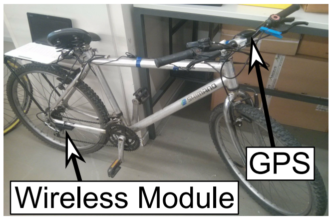

Fig. 1: Experimental setup.

	802.11	802.15.4	Bluetooth EDR
Nominal Rate	1 Mbit/s / 24 Mbit/s / auto-rate	250 kbit/s	3 Mbit/s
Payload	1472B	128B	682B
Reliability	2 re-txs	None	Re-tx until ACK
Conn. type	UDP	n/a	ACL 3-DH5
Offered rate	700 kbit/s / 17 Mbit/s / 40 Mbit/s	40 kbit/s	1.72 Mbit/s

TABLE I: Parameters values used in experiments, per technology.

ours is, to the best of our knowledge, the most in-depth analysis of link performance between bicycles so far.

III. Experiment Technologies and Setup

In this section, we present the metrics and parameters under study in our experiments, and describe the experimental setup of our measurement sessions, in terms of hardware and adopted configurations.

We compare the performance of the three technologies with respect to the following parameters:

- **Communication range**;
- **Throughput** and **packet loss ratio** (PLR).

These metrics are the parameters of most interest to application and network designers.

A. Hardware and Experimental Setup

We used the following wireless modules:

- IEEE 802.15.4: Crossbow TelosB [15], using a TI CC2420 transceiver [16];
- IEEE 802.11g: unidentified WLAN USB dongle, using a Ralink RT5370 chip [17];
- Bluetooth: Trust BT USB dongle, with an Atheros AR3011 [18] chip.

These modules were selected mainly for two reasons: 1) they provide a USB interface, making them compatible with a wide range of embedded platforms; 2) they have a small form factor, a relevant aspect in a bicycle.

The modules were enclosed in a plastic box and securely fastened just above the bike chain. This location was selected following product-driven reasons: the chain is often enclosed in a protective casing, and the space within that case is unimpeded and of reasonable volume. For companies and developers, these characteristics make this space a preferential place to install hardware such as batteries and electronic components. A product using this placement is found in [19].

A USB GPS receiver installed in the handlebar logged the bicycle's position. Wireless and GPS modules were connected to a laptop placed on a carrier above the rear wheel, using meter-long USB cables. This laptop recorded the logs. Fig. 1 shows the setup.

B. Communication and Measurement Parameters

The main configuration parameters used in these experiments are summarized in Table I. In all technologies, the communication flow was set to be unidirectional, from a moving transmitter bicycle (Tx-bicycle) to a standing receiver one (Rx-bicycle). In all setups, data is created at a rate that fills up the channel. In an effort to measure actual link capacity, we deactivated or limited all error recovery mechanisms to the extent possible.

For IEEE 802.11 (WiFi), we set the module to *ad-hoc* mode to avoid association, and the threshold of long frame retries to 2 to reduce re-transmission overhead. We tested three physical-layer bit rate setups: automatic rate adaptation (for convenience, referred also as *auto-rate*) and fixed at 1 and 24 Mbit/s. Both nodes were configured to the same channel, and IP addresses were fixed. The measurement software was iPerf [20] 2.0.5. We found experimentally that generating data on iPerf at 40Mbit/s keeps the channel permanently busy, either for *auto-rate* and fixed 24Mbit/s rates, while for the fixed rate of 1 Mbit/s it was enough to offer 700kbit/s. This defines offered rate. The UDP transport protocol was used to minimize overhead caused by reliability schemes and avoid the impact of the congestion control mechanism.

The measurement software for the IEEE 802.15.4 platform was composed of sender and receiver services developed on the TinyOS operating system/programming environment. The packet size was set to the maximum in the standard, and packets were broadcasted. In TelosB nodes, the offered rate can be adjusted by setting the inter-packet interval. We tested several values in the laboratory, and we found 20ms to be the minimum interval for which PLR is close to zero, yielding an offered rate of 40kbit/s. We removed ACK packets to minimize retransmission overhead.

In Bluetooth, discovery overhead was minimized by informing both devices of the peer ID prior to the experiment. We maximized link throughput using the longest packet type (3-DH5) and longest payload size. Tests were carried out with a modified version of the *l2test* [21] application, that operates over *L2CAP* and the ACL link layer. We offered load to the link at 1.72 Mbit/s, which we confirmed experimentally to keep the channel busy. The ERTM reliable transfer mechanism was used, because it was not possible to turn it off.

IV. Experimental Link Characterization

A. Methodology

The experiments were carried out in an empty parking lot and in a pedestrian area. The two bicycles were aligned along parallel lines with a constant perpendicular distance of 1m. The receiver vehicle (Rx-bicycle) stood

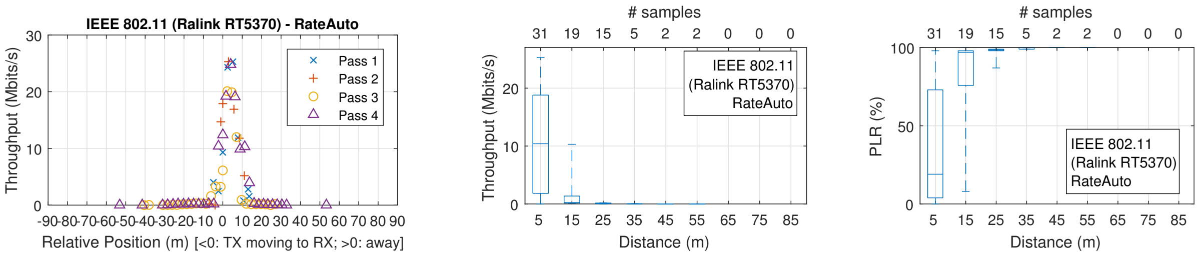

Fig. 2: Raw throughput samples (left), boxplots of throughput and PLR (mid/right) for IEEE 802.11 in auto-rate.

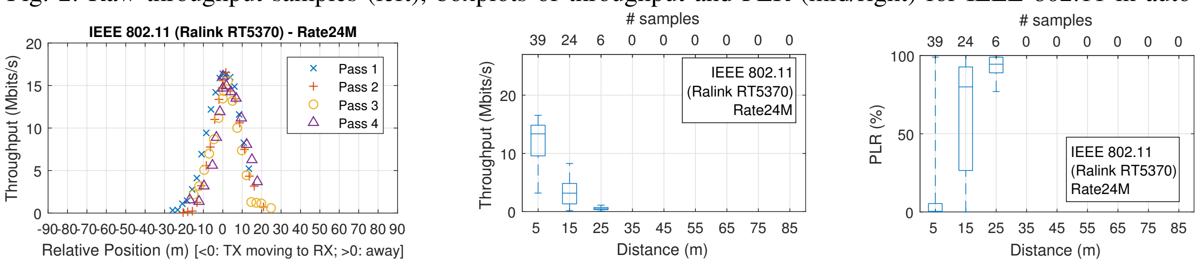

Fig. 3: Raw throughput samples (left), boxplots of throughput and PLR (mid/right) for IEEE 802.11 at 24Mbit/s.

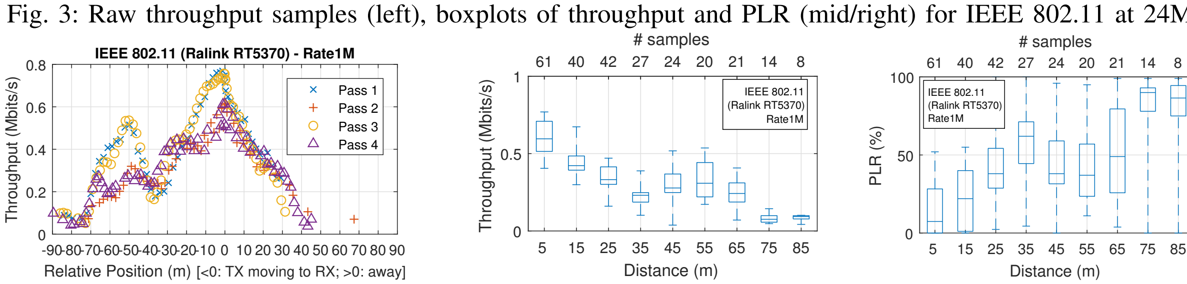

Fig. 4: Raw throughput samples (left), boxplots of throughput and PLR (mid/right) for IEEE 802.11 at 1Mbit/s.

at a fixed location throughout the entire experiment. During the experiment, the transmitter bicycle (Tx-bicycle) was placed out of range (for the technology in study), started its movement along a straight line towards the Rx-bicycle, and then continued away from it, until moving out of range. We carried out this procedure four times per technology. In turns, the bicycles were facing opposite and same directions.

B. Results

The results for each technology are shown in Fig. 2 to 6. The collected samples were smoothed with a moving average filter of span 5 except for IEEE 802.11 in auto-rate. In this case, we observed that smoothing would remove relevant points due to the fast variation of measured throughput. For all 5 technologies, the most relevant finding was that **performance depends more on whether the Tx-bicycle is approaching/ moving away from the Rx-bicycle**, than on whether the Tx-bicycle is at the front/back of the Rx-bicycle. To account for this effect, we present the range and throughput results according to the first criteria. The negative x-axis represents distance between the bicycles, while *approaching* the Rx-bicycle, and the positive x-axis represents the distance between the bicycles while moving *away* from it. The average velocity of the Tx-bicycle was 2m/s, measured by GPS. Finally, we define the communication range as the absolute distance within which the average throughput stays above 10% of the maximum observed value in at least one of the directions. Our findings are:

IEEE 802.11 with auto-rate [802.11@AR] (Fig. 2): When set to automatic adjustment of bit rate, IEEE 802.11 achieves transfer rates close to 25Mbit/s. The communication range (as defined above) was limited to 10 meters, and few packets went beyond 40 m. This limitation has been previously observed by other authors [22]. Mobile nodes have typically faster dynamics than the time taken to find the best bit-rate by the rate adaptation algorithm.

IEEE 802.11 at 24**Mbit/s** [802.11@24] (Fig. 3): In this case, peak transfer rate is close to 17 Mbit/s. Communication range is around 15m with no successful transfer after 30 m. Comparing with the previous case, the range is slightly larger, and so is the throughput observed, while exhibiting a slightly lower PLR.

IEEE 802.11 at 1**Mbit/s** [802.11@1] (Fig. 4): Peak throughput is close to 800kbit/s, and the observed communication range is 40m, but there is a significant asymmetry in the directions. There are successful packet transfers at 90m when approaching the standing bicycle, but only up to 45m when moving away.

IEEE 802.15.4 [802.15.4] (Fig. 5): Peak throughput is 50kbit/s, and the communication range is around 30m. The behavior with distance is constrained when moving

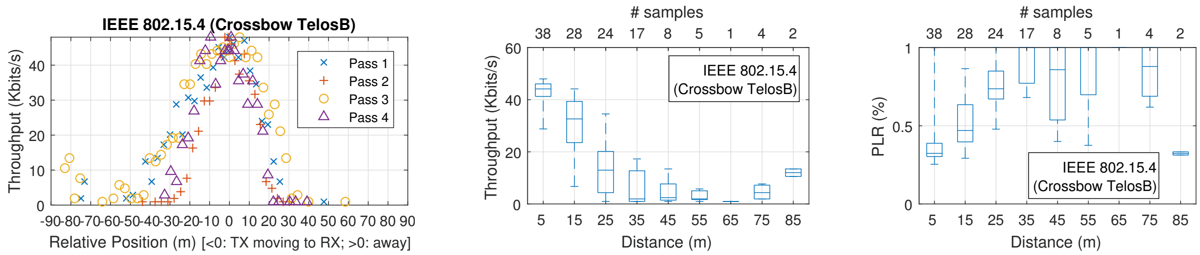

Fig. 5: Raw throughput samples (left), boxplots of throughput and PLR (mid/right), for IEEE 802.15.4.

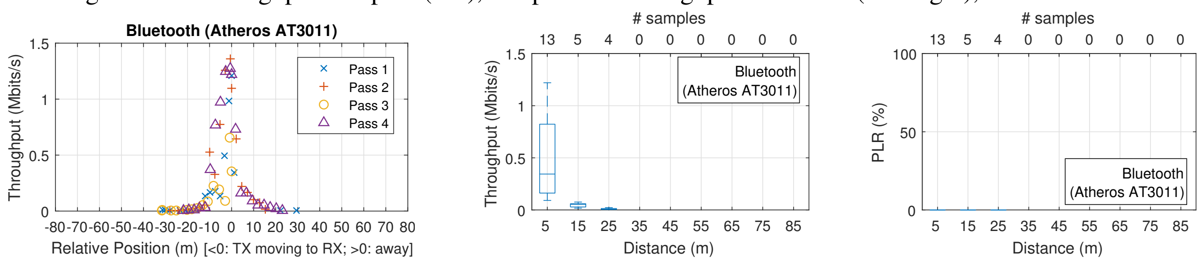

Fig. 6: Raw throughput samples (left), boxplots of throughput and PLR (mid/right), for Bluetooth.

away from the standing Rx-bicycle, similarly to IEEE 802.11 at 1Mbit/s; there are successful packet transfers since 90m when approaching, but only up to 40 m when moving away.

Bluetooth [BT] (Fig. 6): Throughput reached near 1.4Mbit/s. Communication range roughly reached 10m, with only very few packets overcoming 20m. As in the previous cases, communication is possible over larger distances when approaching the Rx-bicycle than when moving away. Packet loss rates reported by Bluetooth are zero, due to not being able to turn off the ERTM retransmissions mechanism.

C. Performance Overview of 2.4 GHz Technologies

The results allow us to build a comprehensive image of the performance of the several technology setups. We compare them by communication range (as defined in previous section), transfered data volume per contact (average), and power consumption when transmitting. The power consumption measurements of the modules were carried out in laboratory, using a Monsoon Power Meter [23]. Measurements were collected over three 30s-long sessions per technology.

Fig. 7 depicts the global view. We aggregated technologies into three clusters according to their most distinctive feature:

(A) **High volume:** 802.11@AR and 802.11@24M – provide high data volume at the cost of short range and large power consumption; 802.11@24M outperforms 802.11@AR with little energy overhead;

(B) **Low-power consumption:** BT – oriented for power-constrained, low range and volume usages;

(C) **Long range:** 802.15.4 and 802.11@1M – reach the furthest; 802.11@1M outperforms 802.15.4 in range and volume while being more power-hungry.

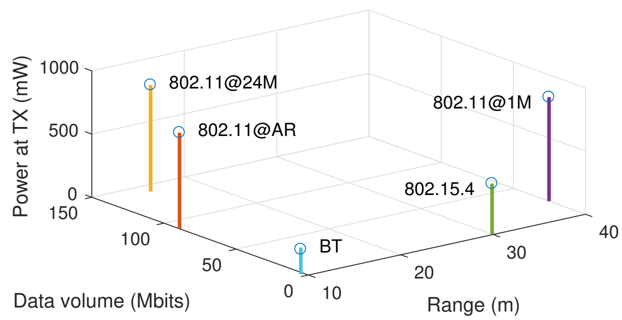

Fig. 7: Performance overview of wireless technologies.

V. Discussion on 2.4 GHz Bi2Bi Links

In this work we present a first look into the reality of Bi2Bi connectivity using 2.4 GHz technologies. On one hand, our results enable the identification of technologies that best suit a target application, thus being useful for network and application designers. On the other hand, the performance of Bi2Bi links depends on a range of factors that were only briefly addressed in this article and that warrant further study. We discuss some of such aspects, informed by our experiences and results.

A. Applications and Suited Technology

In Table II, we propose a taxonomy of applications for Bi2Bi scenarios. Our results enable the assessment of which technologies (clustered in Section IV-C) are best per application type.

Social – Low-latency exchange of text or audio messages, e.g., group audio chat or voice-mail. In the case of bicycle platoons, cyclists can often spread across hundreds of meters, and environment and wind noise rapidly deteriorates spoken communication. Audio applications require high bandwidth at short distance, and thus Cluster (A) technologies would be a good fit.

Infotainment – Information with limited utility lifetime (but not urgent), e.g., news and traffic. The envi-

	Data Volume	Latency	Reach
Social	Medium (20KB)	Low (ms)	Platoon
Infotain.	High (100KB)	Medium (min)	Passerbys
Safety	Small (100B)	Low (ms)	Street/Block

TABLE II: Taxonomy for Bi2Bi applications.

sioned scenario involves traffic reports and details about events for cyclists (e.g., memorabilia fairs, bike tours) being presented in a media of choice (small LCD, ear-piece). Data can be disseminated over multiple hops or in a delay-tolerant fashion, so range needs not to be large. Bluetooth (the Cluster (B) technology) is a good option.

Safety – Communication of critical messages to avoid collisions with other vehicles. Range should be large to reach as much road-users as possible in a timely fashion. Messages can be small (e.g., position and direction vector). Cluster (C) comes through as the best option.

B. Challenges and Limitations

This initial study left open several challenges of Bi2Bi link performance.

Antenna positioning is more complex than in cars, and potential positions in a bicycle exhibit a number of limitations, e.g.: 1) under the seat: attenuation by seat and frame; 2) handlebar (center): human shadowing; 3) chain area: impact of wheel spokes. All of these are likely to lead to anisotropic radiation on the horizontal plane, dependent on the chosen antenna position. The impact of the position must thus be carefully studied.

Antenna orientation, type, polarization influence the radiation pattern of the bike+rider agglomerate. However, the frame imposes constraints on the location and orientation, as well as near field occupation.

Relative positioning of bicycles can significantly impact the link performance, and should be considered in models. As an example, consider the scenario of two side-by-side bicycles. The link may be in situation of: 1) line of-sight, if the modules are on the facing sides of each bicycle; 2) large attenuation, if the modules are on opposing sides of the frames; or 3) an intermediate situation, if one module is on the facing side and the other on the opposing side.

Frame form and material contribute to variability of the radiation patterns. Accessories like rear rack or front basket may introduce additional attenuation.

VI. Conclusions and Future Work

We experimentally characterized the performance of wireless technologies that operate in the ISM band of 2.4GHz for bicycle-to-bicycle (Bi2Bi) links using off-the-shelf commodity hardware. We evaluated range, throughput and packet loss ratio of five technology setups. The main take aways are: 1) that well-established technologies in the 2.4 GHz ISM band enable a multitude of applications for Bi2Bi networks; 2) that whether bicycles are approaching or moving away is a major factor affecting link performance in our settings.

Future work will develop a model of Bi2Bi communication that takes into account the findings in this paper, and addresses the challenges identified, such as characterizing the anisotropic radiation pattern of bicycles being ridden. This later aspect is particularly unexpected, and experiments to characterize it more accurately are planned. We ultimately aim at developing a generic model of Bi2Bi throughput performance, not restricted to parallel scenarios.

Acknowledgments

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