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Can You Hear Me?
A Metric for Link Asymmetry

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ABSTRACT

The Internet of Things is a networking paradigm aiming to provide computing pervasiveness to our everyday lives. A key component to the Internet of Things is low power networks that gather information from the environment. Low power networks are prone to asymmetric and unidirectional links. Measuring the level of asymmetry and understanding its sources are key steps to successfully deploying sensor networks and the Internet of Things. Our first contribution is a new metric to assess link asymmetry, one which takes into account the instantaneous delivery success probability. Next, we study the influence of four factors on link asymmetry in light of our asymmetry metric, namely, relative distance, output power, relative position, and hardware heterogeneity. With our unique method, we show that all four factors impact link asymmetry.

TYPE OF PAPER AND KEYWORDS

Experiments and Analysis: *link asymmetry, evaluation metrics, testbed experiments.*

1 INTRODUCTION

Network protocol designers usually assume a bidirectional, symmetric link layer. Although a reasonable assumption for wired networks, since cables are reliable and often-times dedicated to a node pair, wireless networks face a different reality.

Wireless communication depends on clear radio signals to decode incoming packets. Therefore, a wireless communication link may become asymmetric – or even unidirectional – due to unbalanced conditions at the receiver of each communicating node.

Examples of factors that cause receiving condition disparities are: 1) meteorological conditions, 2) non-isotropic antenna radiation patterns [17], 3) differences in transmission power, and 4) multipath fading.

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One of the core Internet of Things (IoT) components is a data-harvesting Wireless Sensor Network (WSN) [1]. A WSN is composed by simple resource constrained devices, with limited energy supply, reduced processing capabilities, and low data transmission rate. WSNs, also denominated low power and lossy networks (LLNs), use communication protocols tailored for its limitations, such as the IEEE 802.15.4 standard [7].

The effect of asymmetry-causing factors tends to be magnified in LLNs, since 1) the devices are low cost, incurring in low quality transceivers, 2) LLNs are multi-hop and device placement is not carefully planned, and 3) different device models may have non-conforming output powers and receiver sensitivities, whereas device heterogeneity is an IoT trait [1]. For example, CC2420 radio power output ranges from -25 to $0\ dBm$ [15], while CC2650 radio power output ranges from -9 to $5\ dBm$ [16].

Whichever is the asymmetry source, it affects link quality metrics, such as the signal to noise ratio (SNR), link quality estimator (LQI), and packet delivery rate (PDR). Nonetheless, assessing the magnitude of link asymmetry from these metrics is not a trivial task, as we discuss in the related work section (Section 2).

Therefore, our goal is to characterize the occurrence of asymmetric links in LLNs. Our contribution is twofold: 1) we devise a metric for quantifying link asymmetry in Section 3; and 2) we provide a method tailored for assessing link asymmetry and perform numerous tests with the goal of understanding the causes of link asymmetry in an indoor testbed (Section 4). Although we apply our metric to LLNs, it may be applied to any networked system, since its definition is generic.

The experiment results in Section 5 show that link asymmetry occurs even in homogeneous networks. Heterogeneity factors further increase network asymmetry, potentially leading to highly asymmetric links. We present our final remarks in Section 6.

2 RELATED WORK

In this section, we discuss some prior work that investigates wireless link asymmetry.

Wireless link asymmetry is related to link quality assessment, so we turn to the survey by Baccour *et. al* [3]. According to the authors, most link quality assessment methods are either receiver or sender-sided. Consequently, they do not take link asymmetry into account.

Two exceptions found in the survey are the Expected Transmission Count (ETX) and the Fuzzy Link Quality Estimator (F-LQE). The ETX metric [5] estimates the link quality as $\frac{1}{PDR_{AB}*PDR_{BA}}$, where PDR stands for packet delivery rate. Therefore, the lower the ETX estimation, lower are the chances of link asymmetry, since, given an ETX estimation, the maximum PDR difference is $1-\frac{1}{ETX}$. However, the actual maximum PDR difference may be any value in the interval $[0, 1-\frac{1}{ETX}]$, making it inappropriate as an asymmetry metric, especially for higher ETX values.

F-LQE [2] uses fuzzy logic to combine packet delivery, link asymmetry, link stability, and channel quality. They defined asymmetry as the difference between the averaged delivery ratios, $|PDR_{AB} - PDR_{BA}|$. We show this method is inappropriate in Section 3.

Sang et al. [13] proposed ETF (expected number of transmissions over forward links), a link quality assessment method that can be used on unidirectional links. Although the objective is not to quantify link asymmetry, the authors performed several experiments to study the link asymmetry phenomenon. Our experiments differ from Sang et al. in the three primary aspects: 1) they sample 100 packets at $1Hz$, 2) their packet transmissions are not synchronized nor intertwined, 3) the frequency band they tested is $433MHz$.

Luo et al. [11] use a machine learning method to classify link quality into 5 categories: very bad, bad, common, good, or very good. They take into account RSSI, LQI, and SNR, all physical layer indicators. Although their method considers forward indicators values and backward indicators values separately, the final metric value does not reflect the level of link asymmetry.

Gangzhou et al. [17] studied the effect of non-isotropic antennas with Mica2 motes (CC1000 radio, operating at $433Mhz$). Although they did not create an asymmetry metric, they showed that antenna rotation, battery level, and random manufacturing-effects play a role on link asymmetry, represented by the dispersion of RSSI values. Similar to Sang et al. [13], they used a small non-intertwined sample (100 packets).

Srinivasan et al. [14] provided a thorough analysis on low power wireless characteristics. Section 8 of their work, in particular, studies link asymmetry. Although they experiment on the $2.4GHz$ band, their experiments are only 2-second long, hindering the drawing of further conclusions.

Other studies focused on the IEEE 802.11 standard. For example, Overlay MAC Layer (OML) protocol [12] implements a procedure to increase medium access fairness in the presence of link asymmetry. Judd and Steenkiste [9] study many characteristics of IEEE 802.11 standard links. They investigate link asymmetry by measuring signal attenuation; however, a specific metric was not designed. Kotz et al. [10] enumerates six axioms that researchers often mistakenly take as granted; one of them is considering links are always bidirectional and symmetric. They perform experiments using signal strength quotient as the asymmetry metric; but their experimental method is not clear.

The research gap filled by this article is represented by the absence of a metric to quantify link asymmetry, lack of experiments on the $2.4GHz$ band in the literature, and the need of a dedicated method to assess link asymmetry. A method and a metric dedicated to assess asymmetry is instrumental to reveal the true characteristics of links, since the methods in the current state of the art tend to underestimate or to be imprecise.

Events at Node A O O O O x x x x
Events at Node B x x x x O O O O
----------------→ *time*

Figure 1: Corner case example. Circles represent successful packet delivery, the letter x represents delivery failure

3 THE METRIC

Let us assume the existence of a metric $m \in [0, 1]$ able to capture the asymmetry of a link between nodes A and B, with $m = 0$ meaning perfectly bidirectional, and $m = 1$ meaning completely unidirectional.

Intuitively, in a completely unidirectional link, node A delivers 100% to node B, but node B cannot deliver anything to node A. Analogously, an example of a perfectly bidirectional link is a link which delivers 100% in both directions.

A simple way to calculate m, bearing in mind the aforementioned criteria, would be $m = |PDR_{AB} - PDR_{BA}|$, where PDR stands for packet delivery rate, the subscript indicates the the assessment direction, e.g., AB is the delivery rate of packets transmitted from A to B, and $|.|$ is the absolute value function.

However, this definition is problematic if the underlying delivery probability changes over time. For example, take the corner case shown in Figure 1. According to the previous definition of m, this link would not be asymmetric at all, since $m = |PDR_{AB} - PDR_{BA}| = 50\% - 50\% = 0$.

However, a perfectly symmetric link does not match the intuitive expectations when observing the events in Figure 1, in this particular order. The time distribution of events should be taken into account to provide a more accurate assessment of the asymmetry.

Therefore, we define the link asymmetry metric, m, as the absolute value of instantaneous delivery probability difference, averaged during the observation time. Equation 1 comprises this definition, where DP(t) is the instantaneous Delivery Probability at time t, t_i and t_f are the initial and final observation times.

$$m = \frac{\int_{t_i}^{t_f} |DP_{AB}(t) - DP_{BA}(t)| dt}{t_f - t_i} \tag{1}$$

Estimating the unknown delivery probability DP(t) is a non-trivial task. As a simplistic example, considering the event trace presented in Figure 1, let us define $DP(t) = 1$ if closest event in time is successful delivery, and $DP(t) = 0$ otherwise.

This definition yields the delivery probability over time shown in Figure 2, assuming evenly spaced events. This results in an asymmetric index $m \approx 0.93$, indicating that our metric captures the unidirectionality of the link.

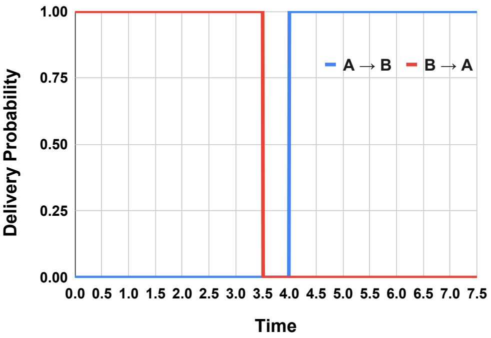


Figure 2: Example of delivery probability over time

The method to estimate the DP(t) can be arbitrarily complex, including multiple variables and statistics. We describe the method used in this paper, which we believe compromises between complexity and accuracy, in Section 4.

4 METHOD

To properly characterize the occurrence of unidirectional links in LLNs, we performed experiments with a pair of nodes transmitting packets to each other. We implemented the test software on Contiki OS 3.0, using the unreliable unicast primitive from the RIME stack [6], without any duty cycling mechanism. All experiments use IEEE 802.15.4 [7] 2.4 GHz compliant radios.

Each node transmits unicast sequenced packets at fixed intervals Δt; the transmission schedules are shifted $\frac{\Delta t}{2}$ from each other. We empirically chose $\Delta t = 100ms$ in 1-hour long experiments.

We used a sliding window technique to estimate delivery probabilities $DP(t)$. First, the packet reception data is converted to a vector $delivery$ of length 36000 filled with 0s (packet not delivered) and 1s (success delivery). At the moments a packet transmission occurred, the delivery probability is calculated as shown in Equation 2, using a quadratic weight function $weight(x) = \frac{w_m - 1}{w^2} x^2 + 1$, in which w_m is the minimum weight, and w is the window's length. We used $w_m = 0.1$ and $w = 3$. We chose a quadratic function as the weight function to model an accelerated decrease of surrounding samples influence on the instantaneous value. We set the numeric parameters empirically. We considered using a method to estimate a variable parameter from a binomial distribution [8]; however, we opted for a simpler method.

Table 1: Parameters Values

Factor	Values
Distance	close, moderate, far
Power level	1-1, 1-2, 3-3, 3-4, 7
Positioning	Left-Right, Bottom-Top, Top-Bottom
Hardware	TelosB-TelosB, TelosB-SensorTag

$$DP(t) = \frac{\sum_{i=t-w}^{t+w} weight(i-t) * deliver(i)}{\sum_{i=t-w}^{t+w} weight(i)} \quad (2)$$

The delivery probability is linearly interpolated on the time instants between packet transmissions. The resultant $DP(t)$ are fed into Equation 1 to calculate the asymmetry metric, m.

We investigated the influence of four factors on link asymmetry. These factors are: 1) node relative distance, 2) transmission power, 3) nodes relative positioning, and 4) node heterogeneity. Other factors are thought to influence link asymmetry, but these are generally difficult to control (e.g. multipath fading, external interference, relative humidity). We strive to keep these factors homogeneous by always running the experiments in the same climate-controlled location. The nodes are USB-powered to avoid voltage supply variations.

The range of factor values is displayed in Table 1. We tested several output power combinations. First, we used low transmission power on TelosB motes, enabling small scale experiments. TelosB's radio transceiver, CC2420, has its output power configured by a 4 bit register. Although it is possible to set any value between 0 and 31, only the register values 3, 7, 11, 15, 19, 23, 27, and 31 are documented with dBm power output on the datasheet [15]. We tested the following combinations of register values on TelosB-only experiments: 1-1, 1-2, 3-3, and 3-4.

We positioned the nodes apart at three distances: 1) close, in which PDR is expected to be nearly 100% in at least one of the directions; 2) moderate, in which some packet losses are observed; and 3) far, in which PDR is expected to be low. The actual distances between the pair of nodes depends on the radio power output, as shown in Table 2, and were empirically determined.

The relative positioning of nodes is varied to check the influence of the antenna radiation pattern. We name the relative position as a pair of directions, each direction being the side facing the other mote, according to the convention shown in Figure 3. From all the possible positioning combinations, we chose three: Top x Bottom (TxB), Bottom x Top (BxT), and Left x Right (LxR), as exemplified in Figure 4.

Table 2: Power and distance values

TelosB Power level	Close	Moderate	Far
1	$20cm$	$40cm$	$50cm$
3 ($-25\ dBm$)	$50cm$	$70cm$	$142.5cm$
7 ($-15\ dBm$)	$\approx 6m$	$\approx 11m$	$\approx 14m$

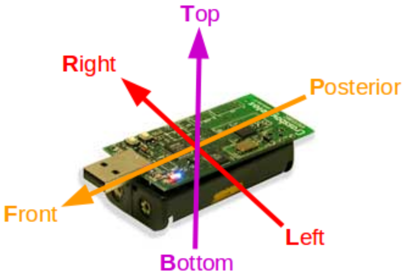


Figure 3: TelosB mote with named radio irradiation directions

The fourth factor is hardware. We test the connectivity between a pair of heterogeneous platforms, a TelosB mote (CC2420 radio) and a SensorTag mote (CC2650 radio). In this set of experiments, we only vary the distance, while setting the power output to $-15\ dBm$ (7, in CC2420 register configuration).

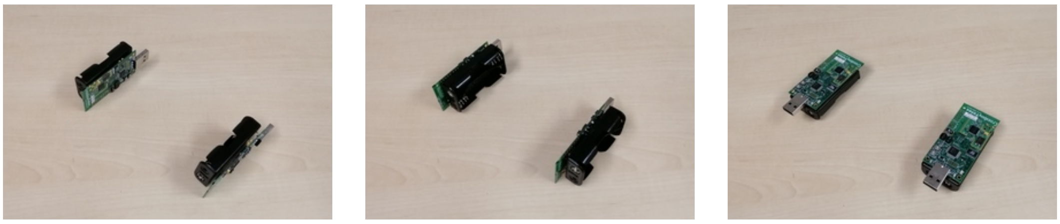
The total number of conducted experiments was 39, accounting for different combinations of distance, power levels, positioning, and hardware. The source code is available at `github.com/rcaalves/linkexperiments`.

5 RESULTS

The experiments' results are presented in tables, with one table for each transmission power combination. Each row refers to the nodes' relative position: Top and Bottom (TxB), Bottom and Top (BxT), and Left and Right (LxR); the position naming convention is defined according to Figure 3 and Figure 4. Each column refers to the distance between the nodes: Close (C), Moderate (M), and Far (F); the actual distances are defined according to Table 2.

Since the asymmetry metric ranges from 0 to 1, we use a color gradient to identify the results, with white cell background color representing no asymmetry and black cell background color representing fully unidirectional.

Table 3 contains results for the power combination 1x1. The only combination with high asymmetry is BxT at the far distance configuration. All the other combinations yielded near null delivery, with exception of LxR-close.



(a) Top x Bottom (TxB) (b) Bottom x Top (BxT) (c) Left x Right (LxR)

Figure 4: Nodes positioning used in the experiments

Table 3: Asymmetry metric values – Power combination 1x1

		Distances		
Positioning		C	M	F
	TxB	0.00	0.00	0.00
	BxT	0.01	0.00	**0.75**
	LxR	0.17	0.07	0.00

Table 4: Asymmetry metric values – Power combination 1x2

		Distances		
Positioning		C	M	F
	TxB	0.13	0.00	0.00
	BxT	0.33	0.00	0.00
	LxR	**0.91**	**0.50**	**0.66**

These results indicate three general findings: 1) Our asymmetry metric is more realistic than delivery rate difference, since LxR-close yielded nearly equal delivery in both directions (85% and 86%), but relatively large asymmetry (0.17); 2) The high asymmetry at BxT-far suggests environmental effects, since shorter distances yielded no delivery in either direction; 3) Node positioning is a determinant factor of link asymmetry and link quality, as the metric values varied sharply in a given column.

As expected, transmission-power imbalance increases asymmetry, as observed in Table 4. Particularly in the LxR position, the node with more transmission power was able to deliver more packets at every distance, while the other node delivered nearly no packets.

However, we observed three notable incongruities comparing the results of Power combination 1x2 to 1x1: 1) BxT-far became symmetric (no delivery in either direction); 2) LxR-close became highly asymmetric because the node with lower power failed to deliver packets; 3) The node with lower power was able to deliver packets in the other close distance cases (TxB and BxT).

Table 5: Asymmetry metric values – Power combination 3x3

		Distances		
Positioning		C	M	F
	TxB	0.10	0.05	0.01
	BxT	0.07	0.05	0.00
	LxR	0.10	0.03	0.00

Since the experiments were executed in the same location, with the same motes powered by USB, effects such as multipath fading, manufacturing variations, and power supply oscillation are unlikely to be reason for the aforementioned incongruities. Rather, external interference is the presumable cause since the experiments were run at different times of the day.

As a consequence, link asymmetry can be seen a transient quality in low power wireless networks. Furthermore, it is unreliable to use a 1-hour long data collection to infer steady state behavior.

Increasing the transmission power to 3 ($-25\ dBm$) in a homogeneous setting reduced the overall link asymmetry to at most 0.1, as observed in Table 5.

Delivery rates were all above 90% on close and moderate distances, but nearly 0% in the far distance configurations. This suggests that increasing the power decreases link asymmetry, since transmissions become less vulnerable to external interference.

Increasing the transmission power of one node affects mostly the far region, as shown in Table 6. Close and moderate distances still presented high delivery rates in both directions, with the exception of LxR-moderate, which delivered no packets in either direction.

The increased power enabled packet delivery in one direction at the far distance, depending on the nodes positioning: TxB, BxT, and LxR yielded 99%, 0%, and 74% delivery. The low power node delivered only a few packets, yielding high asymmetry only in TxB and LxR positions. This variation reinforces the influence of antenna radiation pattern on packet delivery and link asymmetry.

Table 6: Asymmetry metric values – Power combination 3x4

Positioning		C	M	F
	TxB	0.03	0.02	**0.85**
	BxT	0.02	0.08	0.00
	LxR	0.08	0.00	**0.73**

Distances

Table 7: Asymmetry metric values – Heterogeneous setting: TelosB vs SensorTag (-15dBm)

Positioning		C	M	F
	LxR	0.09	0.33	0.01

Distances

Lastly, the node heterogeneity study results are presented in Table 7. The asymmetry at close distance was low, in the same order of magnitude as found in the homogeneous nodes experiments. Low delivery rates in both directions also resulted in low asymmetry at the far distance.

However, at moderate distance, the asymmetry was 0.33, almost 5 times larger than the asymmetry found on the homogeneous experiments with equal transmission power (Table 3 and Table 5). This result suggests that, in comparison to the TelosB mote, the SensorTag mote antenna either presents a different irradiation power or has a higher actual power output.

Overall, the experiments show that all studied factors play a role on link asymmetry to some extent. In particular, we observed that long distance links are more prone to asymmetry than short distance links, telosB nodes transmissions are less powerful at the bottom side, and transmission power heterogeneity or hardware heterogeneity increase the chances of asymmetric links. However, predicting which specific combination of factors would result in a highly asymmetric link is not easily realized by a simple rule of thumb.

Even though the simplistic delivery rate difference would be an accurate asymmetry metric in some cases, our refined metric was able to grasp intricate asymmetry patterns in other cases.

6 FINAL REMARKS

Link asymmetry is an undeniable phenomenon in low power wireless networks. We studied the influence of four factors to link asymmetry, and, to the best of our knowledge, designed the first metric dedicated to assessing link asymmetry.

Each one of the studied factors, distance, output power, relative position, and hardware, plays a non-trivial role in the magnitude of link asymmetry. As IoT and low power wireless networks get larger, it is likely that the deployments become more diverse regarding these factors, increasing the occurrence of highly asymmetric links.

As future work, we would like to extend the experiments to tests an even larger combination of factors, check the influence of the data collection duration, and reproduce the experiments in different times of the day to verify results consistency and reproducibility.

In terms of directions for further study, we suggest investigating the impact of more sophisticated methods to calculate the instantaneous delivery probability, such as using information other than the packet delivery to determine asymmetry level, such as RSSI and LQI [4].

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REFERENCES

[1] L. Atzori, A. Iera, and G. Morabito, "The internet of things: A survey," *Computer Networks*, vol. 54, no. 15, pp. 2787 – 2805, 2010.

[2] N. Baccour, A. Koubâa, H. Youssef, M. Ben Jamâa, D. do Rosário, M. Alves, and L. B. Becker, "F-lqe: A fuzzy link quality estimator for wireless sensor networks," in *Wireless Sensor Networks*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2010, pp. 240–255.

[3] N. Baccour, A. Koubundefineda, L. Mottola, M. A. Zúñiga, H. Youssef, C. A. Boano, and M. Alves, "Radio link quality estimation in wireless sensor networks: A survey," *ACM Trans. Sen. Netw.*, vol. 8, no. 4, Sep. 2012.

[4] C. A. Boano, M. A. Zúñiga, T. Voigt, A. Willig, and K. Römer, "The triangle metric: Fast link quality estimation for mobile wireless sensor networks," in *2010 Proceedings of 19th International Conference on Computer Communications and Networks*, Aug 2010, pp. 1–7.

[5] D. S. J. D. Couto, D. Aguayo, J. Bicket, and R. Morris, "A high-throughput path metric for multi-hop wireless routing," *Wireless Networks*, vol. 11, pp. 419–434, 2005.

[6] A. Dunkels, F. Österlind, and Z. He, “An adaptive communication architecture for wireless sensor networks,” in *Proceedings of the 5th international conference on Embedded networked sensor systems*, 2007, pp. 335–349.

[7] IEEE, “802.15.4-2011 - IEEE Standard for Local and metropolitan area networks – Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs),” 2011.

[8] G. Jensen, “Kernel probability estimation for binomial and multinomial data,” https://doi.org/10.7287/peerj.preprints.1156v1, 2015, peerJ PrePrints 3:e1156v1.

[9] G. Judd and P. Steenkiste, “Characterizing 802.11 wireless link behavior,” *Wireless Networks*, vol. 16, pp. 167–182, 2010. [Online]. Available: 10.1007/s11276-008-0122-5

[10] D. Kotz, C. Newport, and C. Elliott, “The mistaken axioms of wireless-network research,” Dartmouth Computer Science, Tech. Rep. TR2003-467, July 2003. [Online]. Available: http://www.cs.dartmouth.edu/~dfk/research/kotz-axioms-tr/index.html

[11] X. Luo, L. Liu, J. Shu, and M. Al-Kali, “Link quality estimation method for wireless sensor networks based on stacked autoencoder,” *IEEE Access*, vol. 7, pp. 21 572–21 583, 2019.

[12] A. Rao and I. Stoica, “An overlay mac layer for 802.11 networks,” in *Proceedings of the 3rd International Conference on Mobile Systems, Applications, and Services*, ser. MobiSys ’05. New York, NY, USA: Association for Computing Machinery, 2005, p. 135–148.

[13] L. Sang, A. Arora, and H. Zhang, “On link asymmetry and one-way estimation in wireless sensor networks,” *ACM Trans. Sen. Netw.*, vol. 6, no. 2, Mar. 2010.

[14] K. Srinivasan, P. Dutta, A. Tavakoli, and P. Levis, “An empirical study of low-power wireless,” *ACM Trans. Sen. Netw.*, vol. 6, no. 2, Mar. 2010.

[15] *CC2420 2.4 GHz IEEE 802.15.4 / ZigBee-ready RF Transceiver*, Texas Instruments, 2004, (Rev. C).

[16] *Multi-Standard CC2650 SensorTag Design Guide*, Texas Instruments, 2015.

[17] G. Zhou, T. He, S. Krishnamurthy, and J. A. Stankovic, “Impact of radio irregularity on wireless sensor networks,” in *Proceedings of the 2nd International Conference on Mobile Systems, Applications, and Services*, ser. MobiSys ’04. New York, NY, USA: Association for Computing Machinery, 2004, p. 125–138.

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