above showed, PRICAPS cannot guarantee a certain level of anonymity but can rather be seen as a "best effort" approach depending on the number of participating users and their mobility.

Further, our approach does not really incorporate means for coping with different probabilities of certain traces. A highly simplified example is shown in Figure 8a. The solid traces might be more likely than the dotted traces, where both users would take a detour. However, in PRICAPS we assume the sampling rate to be very low, so that each measurement could have been conducted by a large portion of the users and, as a result, there are plenty of possible trace combination, so that a reliable reconstruction of the trace should not be possible.

Another aspect that might weaken the privacy level is the possibility that measurements are too far apart so that it is obvious that they do not belong to the same user. In Figure 8b, a possible scenario is shown for two users. In this case, it seems as there are two users and their traces could be reconstructed. However, the server does not know how many users are currently participating. It could also be the case that this are four different users, so again a reliable trace reconstruction is not possible.

Notice that in all our results, we stated the *worst-case* k-anonymity level, i.e., we calculated the k-anonymity level as if it was known how many users are calibrating. If there are n users with the same calibration vector c and each users adapts m measurements, there are in total $n * m$ updated measurements. In our results, we stated this as k-anonymity level of n. In fact, the server is not aware of the actual amount of users and from the server perspective the updates could originate from a group ranging from 1 to $n * m$ users. As a result, the privacy level should be even higher than our results indicate.

To further improve the results, PRICAPS could be extended by *gamification* features, i.e., users could be incentivised to adapt their mobility. As proposed in [15], users could be rewarded, if they adapt their route in a specified way. This could be used to prompt participants to visit reference stations more often, which would lead to better results regarding data quality and user privacy.

Challenges. A major challenge of realizing PRICAPS is the necessity of appropriate reference stations. This entails that a sufficient amount of stations is required and that those stations have to be reasonably located within the investigation area, so that users pass these sites frequently. Further, as mentioned in 5, we assume reference measurements to be accessible through well-defined web service interfaces. As a consequence, existing stations have to be upgraded or new stations have to be deployed in order to fulfill this requirements. However, building up this infrastructure is very costly and probably takes time.

Another challenge not tackled yet is the consideration of a phone's context when initiating a calibration process. If a mobile phone is in a pocket or bag when approaching a reference station, it is obvious that its measurements deviate from those collected by the station. As a result, calibration tuples should only be recorded if reference station and mobile phone experience the same context. Therefore, a recognition system for the phone's context as in [17] should be incorporated.

7. Conclusion & Future Work

We presented PRICAPS, a system for privacy-preserving calibration system in participatory sensing networks that enables forward as well as backward calibration, while simultaneously protecting the users' privacy. We proposed a pseudonym-based system that allows for transferring calibration parameters to other pseudonyms without revealing the connection between those. Our analysis shows that we can achieve a high degree of anonymity, but only at the price of sacrificing precision. More precisely, the anonymity level and the backward calibration gain are negatively correlated, i.e., an increase of the one leads to a decrease of the other. Our results show that there are several discretization parameters that lead to promising results for both, however, the "optimal" setting depends on the application scenario and the subsequent weighting of anonymity in relation to precision. As the loss of precision is small in relation to the overall gain, we believe that PRICAPS represents a valid concept for privacy-preserving calibration in PSNs.

In future work, we want to evaluate our concept with more extensive simulations using a realistic urban simulation environment and implement a prototype to evaluate the concept in real-life settings.

References

[1] Burke, J., Estrin, D., Hansen, M., Parker, A., Ramanathan, N., Reddy, S. and Srivastava, M.B. (2006) Participatory Sensing. In *Proceedings of WSW'06 at SenSys '06*.

[2] Bychkovskiy, V., Megerian, S., Estrin, D. and Potkonjak, M. (2003) A collaborative approach to in-place sensor calibration. In *Information Processing in Sensor Networks* (Springer Berlin / Heidelberg), *LNCS* **2634**, 556–556.

[3] Campbell, A., Eisenman, S., Lane, N., Miluzzo, E., Peterson, R., Lu, H., Zheng, X. *et al.* (2008) The Rise of People-Centric Sensing. *Internet Computing, IEEE* **12**(4): 12–21. doi:10.1109/MIC.2008.90.

[4] Chaum, D. (1981) Untraceable electronic mail, return addresses, and digital pseudonyms. *Communications of the ACM* **24**(2): 84–90.

[5] Christin, D., Reinhardt, A., Kanhere, S.S. and Hollick, M. (2011) A survey on privacy in mobile participatory sensing applications. *Journal of Systems and Software* **84**(11): 1928 – 1946. doi:10.1016/j.jss.2011.06.073, URL http://www.sciencedirect.com/science/article/pii/S0164121211001701.

[6] Duchon, M., Wiesner, K., Müller, A. and Linnhoff-Popien, C. (2012) Collaborative sensing platform for eco routing and environmental monitoring. In Martins, F., Lopes, L. and Paulino, H. [eds.] *Sensor Systems and Software* (Springer Berlin Heidelberg), *Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering* **102**, 89–104. doi:10.1007/978-3-642-32778-0_8, URL http://dx.doi.org/10.1007/978-3-642-32778-0_8.

[7] Eisenman, S.B., Lane, N.D., Miluzzo, E., Peterson, R.A., seop Ahn, G. and Campbell, A.T. (2006) Metrosense project: People-centric sensing at scale. In *Proceedings of WSW at Sensys'06*.

[8] Ganti, R., Ye, F. and Lei, H. (2011) Mobile crowdsensing: current state and future challenges. *IEEE Communications* **49/11**: 32–39. doi:10.1109/MCOM.2011.6069707.

[9] Hasenfratz, D., Saukh, O., Sturzenegger, S. and Thiele, L. (2012) Participatory Air Pollution Monitoring Using Smartphones. In *Proceedings of the 2nd Workshop on Mobile Sensing: From Smartphones and Wearables to Big Data*.

[10] Hasenfratz, D., Saukh, O. and Thiele, L. (2012) On-the-Fly Calibration of Low-Cost Gas Sensors. In *Wireless Sensor Networks* (Springer Berlin / Heidelberg), *LNCS* **7158**, 228–244.

[11] Honicky, R.E. (2007) *Automatic calibration of sensor-phones using gaussian processes*. Tech. Rep. UCB/EECS-2007-34, EECS, UC Berkeley. URL http://www.eecs.berkeley.edu/Pubs/TechRpts/2007/EECS-2007-34.pdf.

[12] Huan, C., Zhiyu, L. and Gang, F. (2011) Analysis of the aging characteristics of SnO2 gas sensors. *Sensors and Actuators B: Chemical* **156**(2): 912 – 917. doi:10.1016/j.snb.2011.03.005, URL http://www.sciencedirect.com/science/article/pii/S0925400511001870.

[13] Kamionka, M., Breuil, P. and Pijolat, C. (2006) Calibration of a multivariate gas sensing device for atmospheric pollution measurement. *Sensors and Actuators B: Chemical* **118**(1-2): 323 – 327. doi:10.1016/j.snb.2006.04.058, URL http://www.sciencedirect.com/science/article/pii/S0925400506003108.

[14] Lane, N., Miluzzo, E., Lu, H., Peebles, D., Choudhury, T. and Campbell, A. (2010) A survey of mobile phone sensing. *IEEE Communications* **48/9**: 140–150.

[15] McCall, R., Kracheel, M. and Koenig, V. (2012) Reducing Congestion through Persuasive Gaming. In *Proceedings of "The Car as an Arena for Gaming" Workshop at MobileHCI 2012* (San Francisco, CA,).

[16] Miluzzo, E., Lane, N., Campbell, A. and Olfati-Saber, R. (2008) Calibree: A self-calibration system for mobile sensor networks. In *Distributed Computing in Sensor Systems* (Springer Berlin / Heidelberg), *LNCS* **5067**, 314–331.

[17] Miluzzo, E., Papandrea, M., Lane, N.D., Lu, H. and Campbell, A.T. (2010) Pocket, Bag, Hand, etc.-Automatically Detecting Phone Context through Discovery. In *Proceedings of the International Workshop on Sensing for App Phones (PhoneSense 2010)* (Zurich, Siwtzerland): 21–25.

[18] Shepard, D. (1968) A two-dimensional interpolation function for irregularly-spaced data. In *Proceedings of the ACM '68* (New York, NY, USA: ACM): 517–524. doi:10.1145/800186.810616, URL http://doi.acm.org/10.1145/800186.810616.

[19] Sweeney, L. (2002) k-anonymity: A model for protecting privacy. *Int. J. Uncertain. Fuzziness Knowl.-Based Syst.* **10**(5): 557–570. doi:10.1142/S0218488502001648, URL http://dx.doi.org/10.1142/S0218488502001648.

[20] Whitehouse, K. and Culler, D. (2002) Calibration As Parameter Estimation in Sensor Networks. In *Proceedings of the 1st ACM International Workshop on Wireless Sensor Networks and Applications (WSNA '02)* (New York, NY, USA: ACM): 59–67. doi:10.1145/570738.570747, URL http://doi.acm.org/10.1145/570738.570747.

[21] Wiesner, K., Duchon, M. and Dürr, M. (2012) Distributed Multi-Head Clustering for People-Centric Networks. In *Proceedings of the 6th International Conference on Sensor Technologies and Applications (SENSORCOMM 2012)* (Rome, Italy): 53–58. URL http://www.thinkmind.org/index.php?view=article&articleid=sensorcomm_2012_3_10_10142.