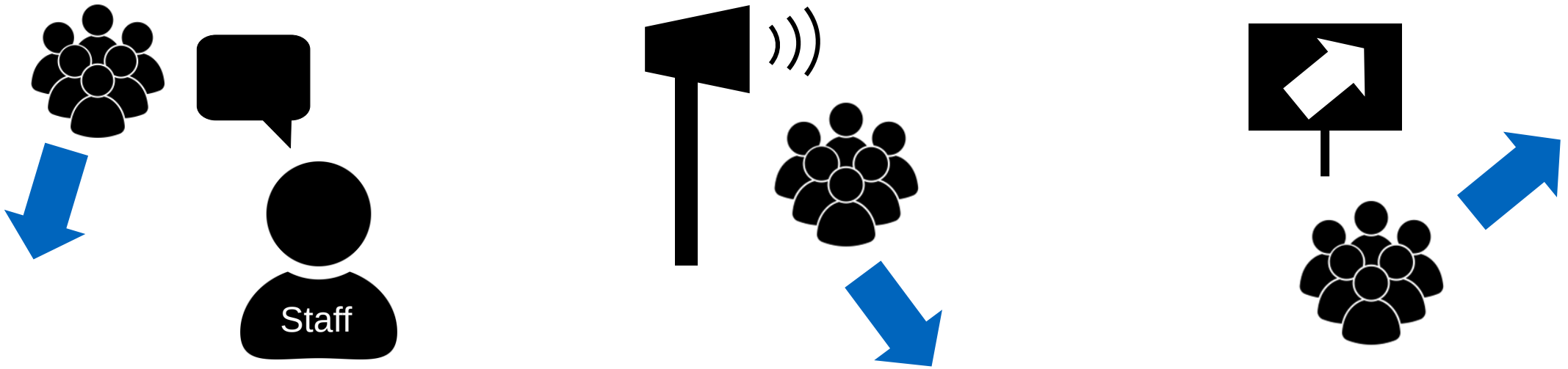
Crowd management based on direct communication technology

Christina Maria Mayr
Doctoral Defense
10th July, 2024

Technical University of Munich
Hochschule München University of Applied Sciences

Crowd management ensures safety and comfort

Several approaches are used in practice [1]



Infrastructure is often missing at transportation hubs

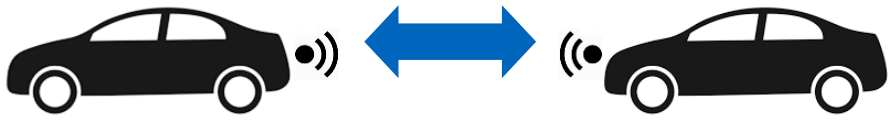
Inform the crowd through mobile applications?

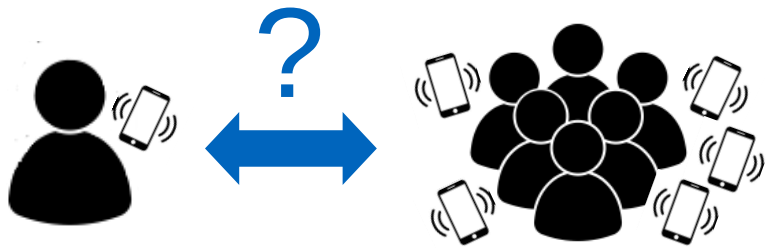
Images: Wolfram Schlenker, rights granted

Direct communication for crowd management applications?

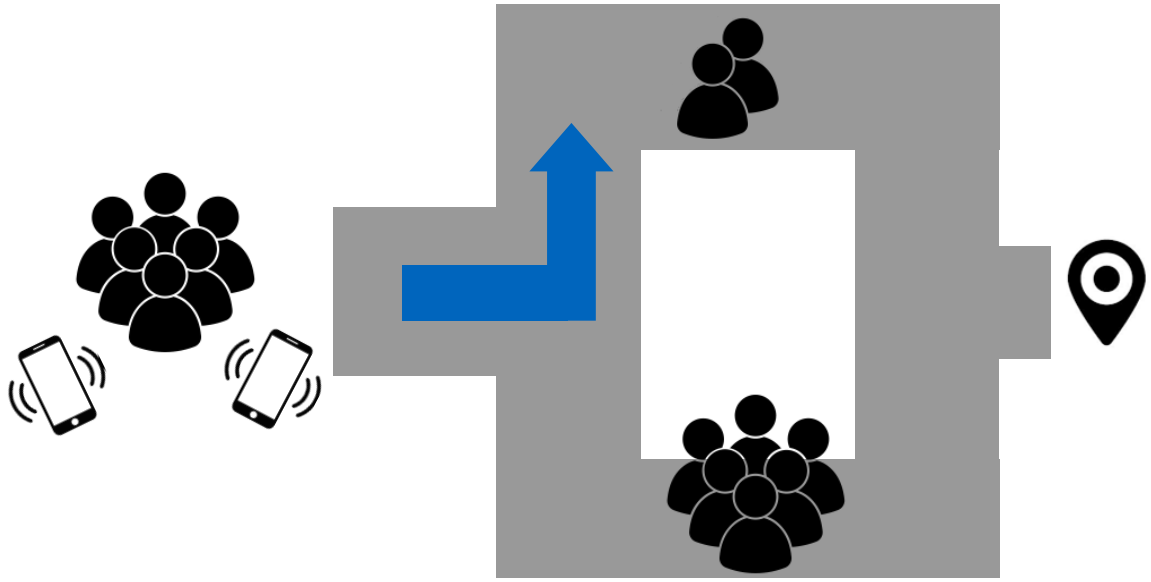
Vehicles exchange data through direct communication technologies.

Example: IEEE 802.11p [2]



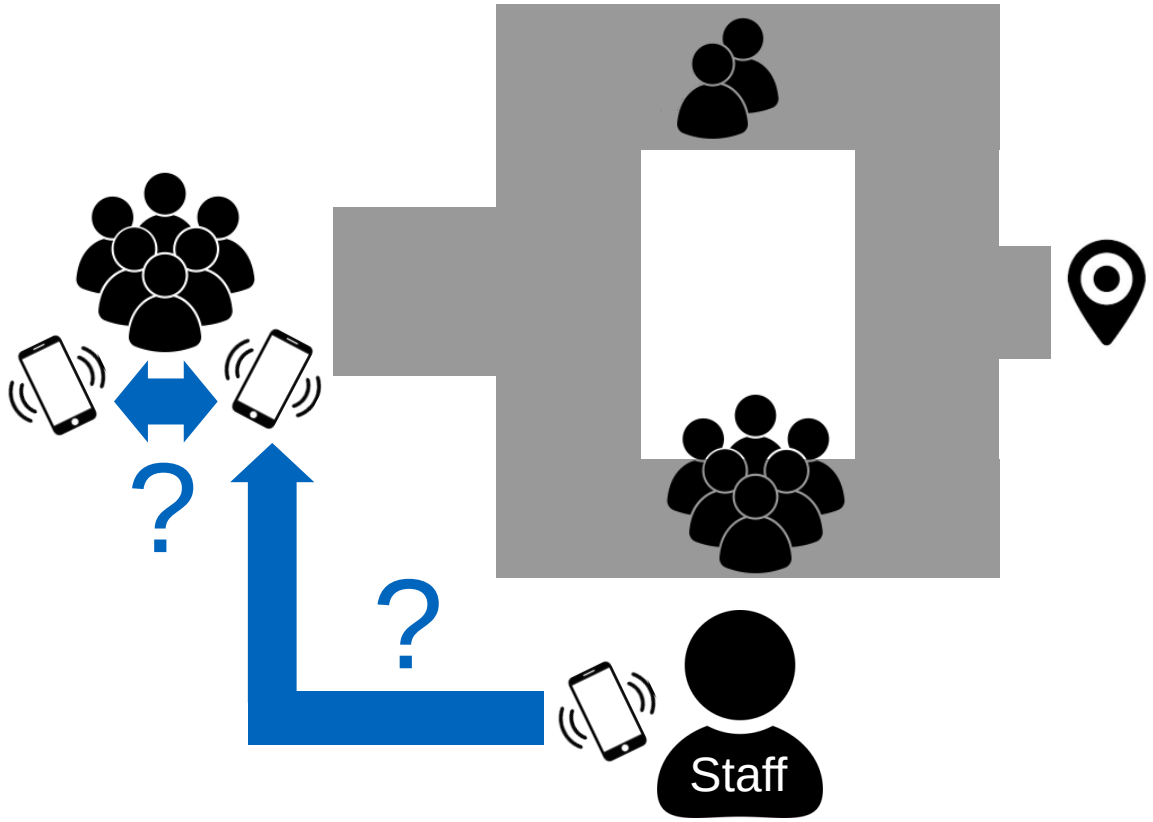


How can crowds be redirected with mobile applications based on direct communication technology?



How can crowds be redirected with mobile applications based on direct communication technology?

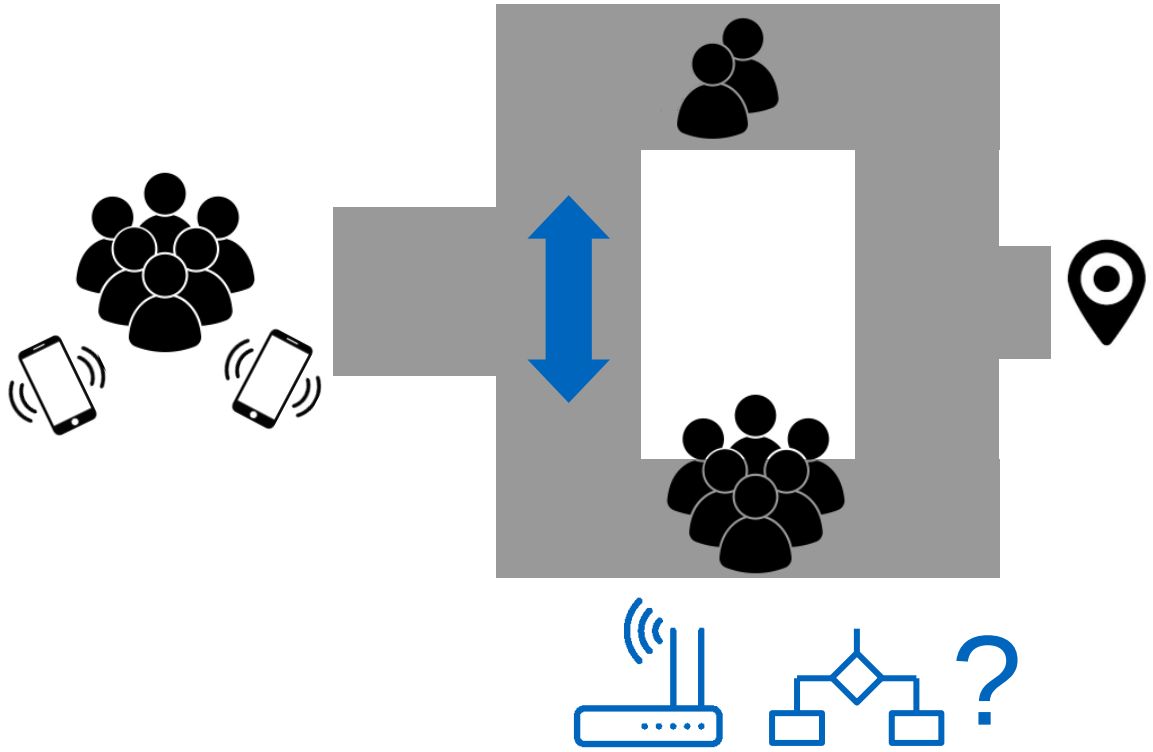
Direct communication technology:
Does the information dissemination work?



How can crowds be redirected with mobile applications based on direct communication technology?

Direct communication technology:
Does the information dissemination work?

Route recommendation algorithm:
Which one is suitable?

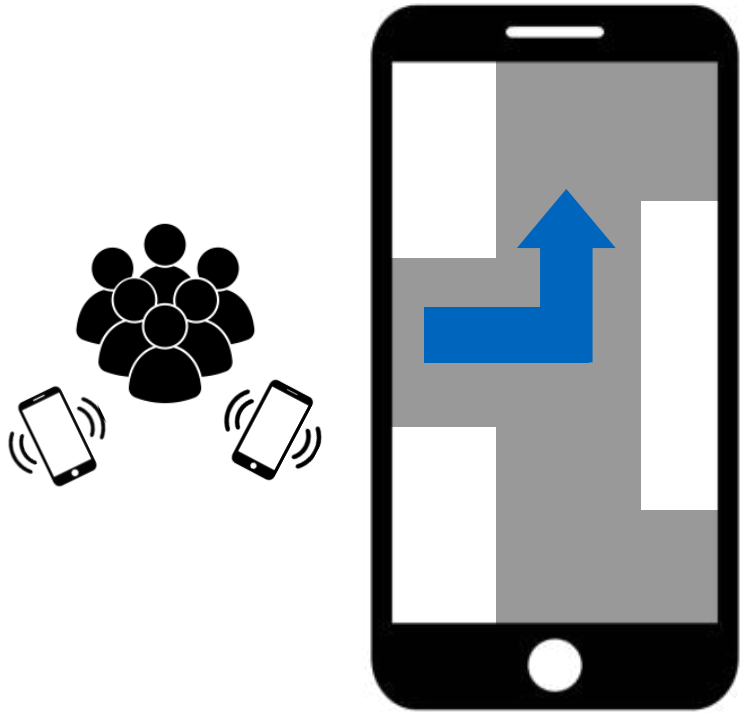


How can crowds be redirected with mobile applications based on direct communication technology?

Direct communication technology:
Does the information dissemination work?

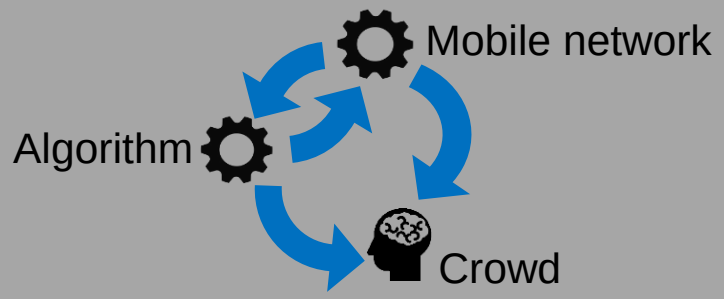
Route recommendation algorithm:
Which one is suitable?

Crowd:
How to design messages to foster compliance?



Focus of today

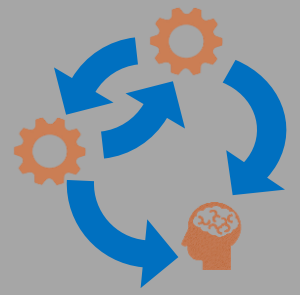
Novel socio-technical system



Component investigation

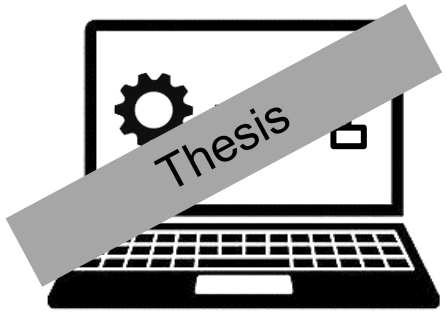
- Algorithm
  Modeling & Simulation
- Mobile network
  Modeling & Simulation
- Crowd behavior
  Survey

Proof of concept

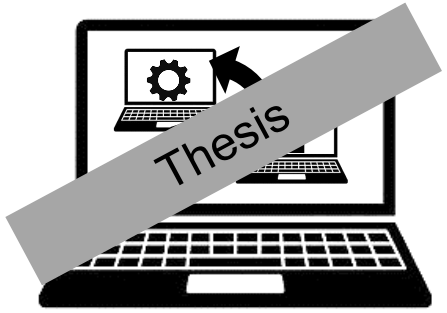


Real life use case

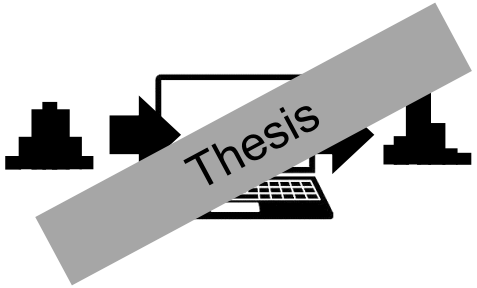
Novel simulator flowcontrol



Novel simulator CrowNet

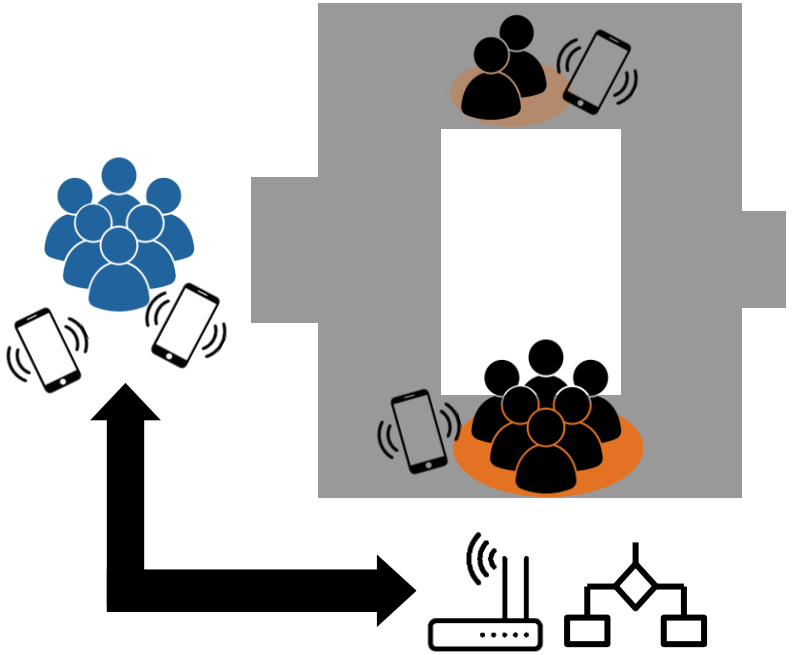


Uncertainty of parameters



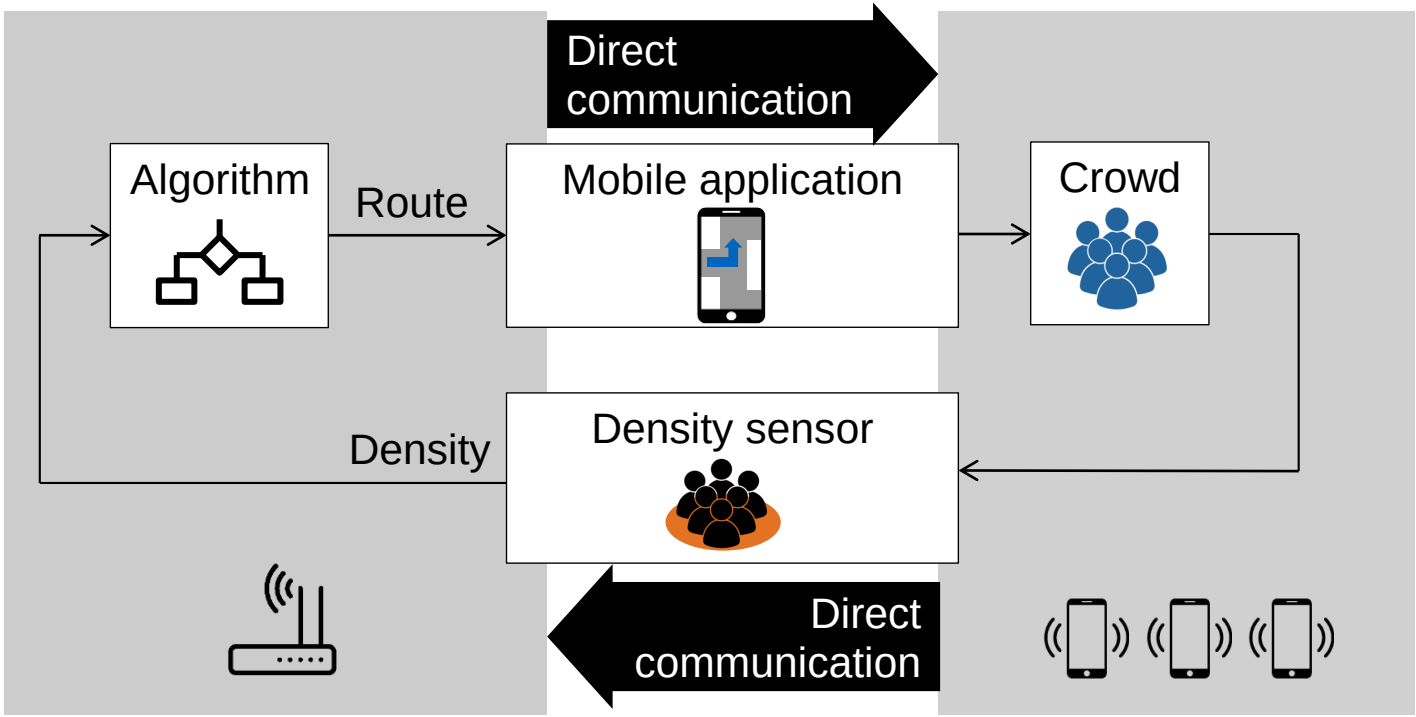
Novel model of a crowd guidance system

Map perspective

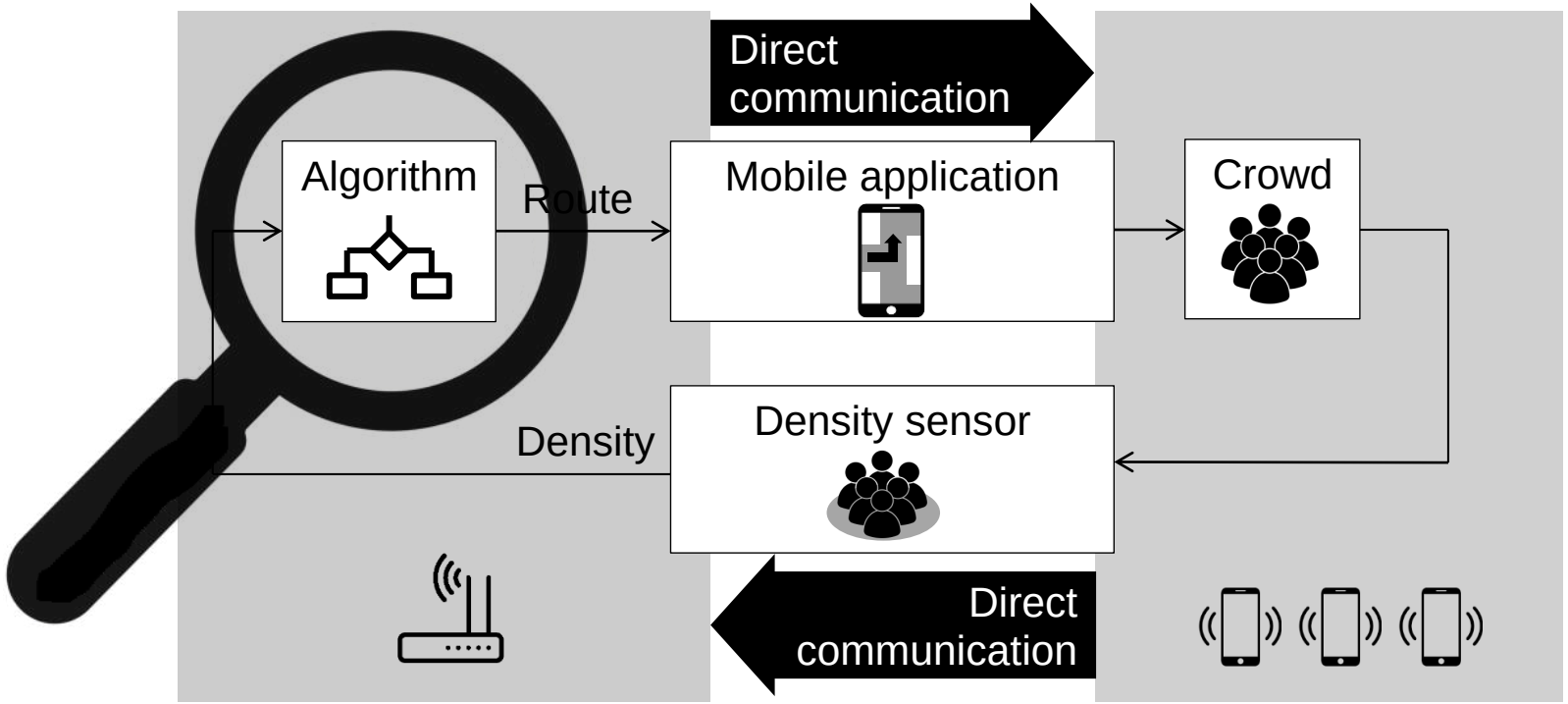


System perspective

See Fig. 3.1 & 4.27 of my thesis

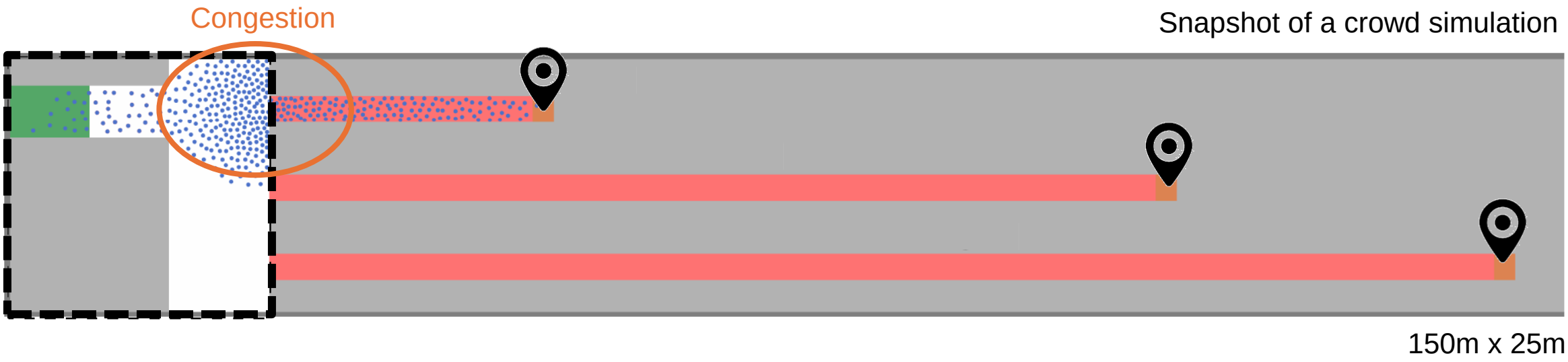


Which route recommendation algorithm is suitable?



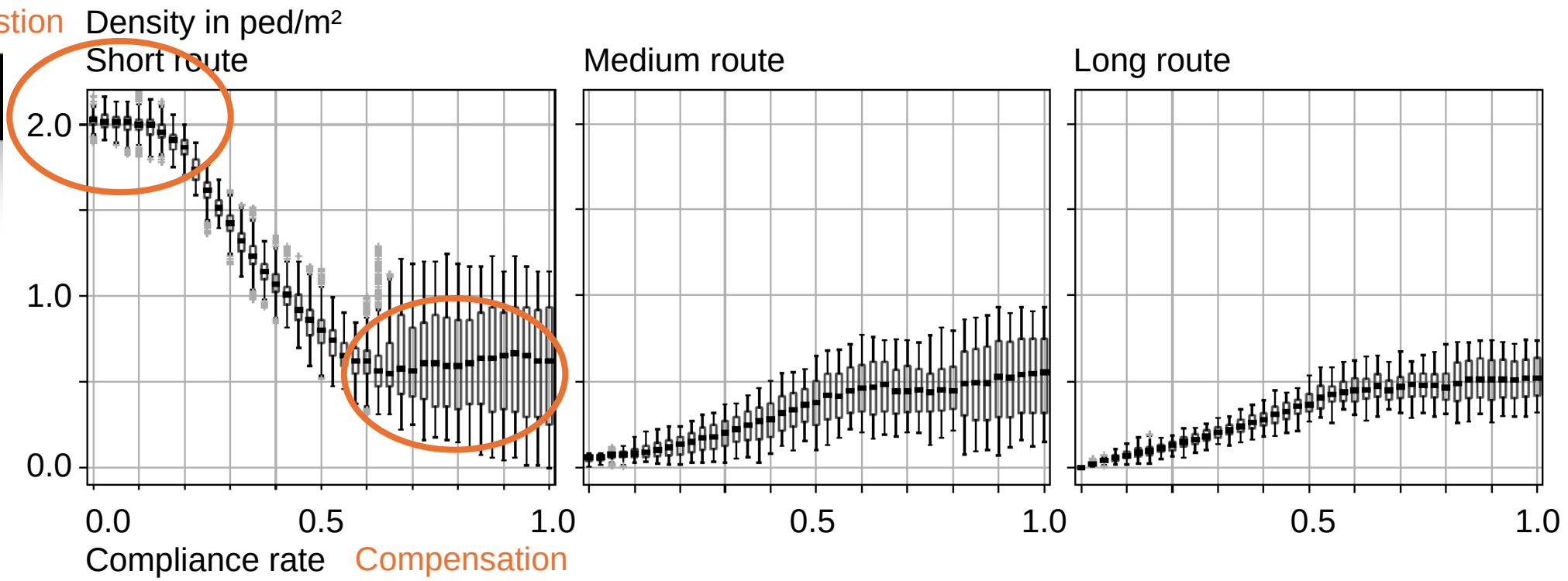
Algorithms have been designed for fully controllable fluids – a crowd does not behave like a fluid!

State-of-the-art algorithms:
Proportional Integral control [7], On-Off-control [8], State-space control [9-12], Model predictive control [13], …



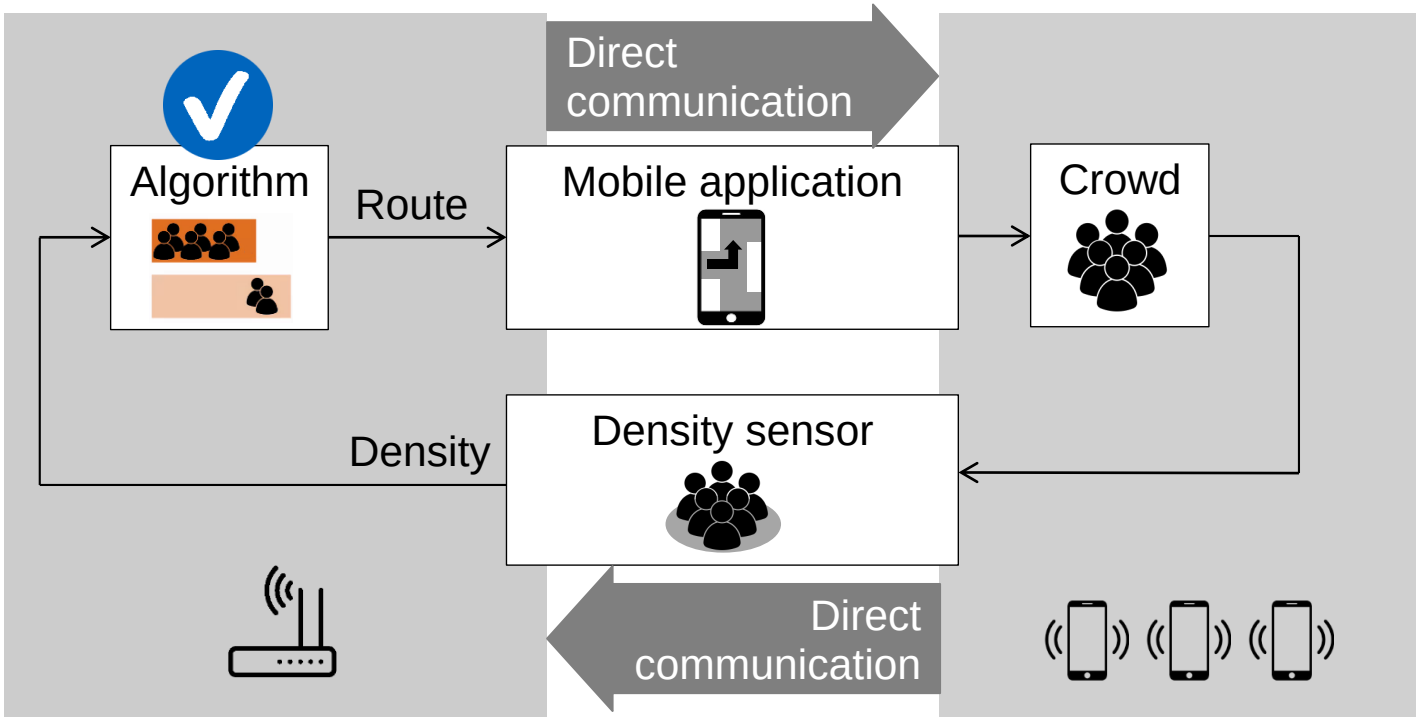
Recommend the route where the density is the lowest

My algorithm resolves congestion and compensates missing compliance [6]

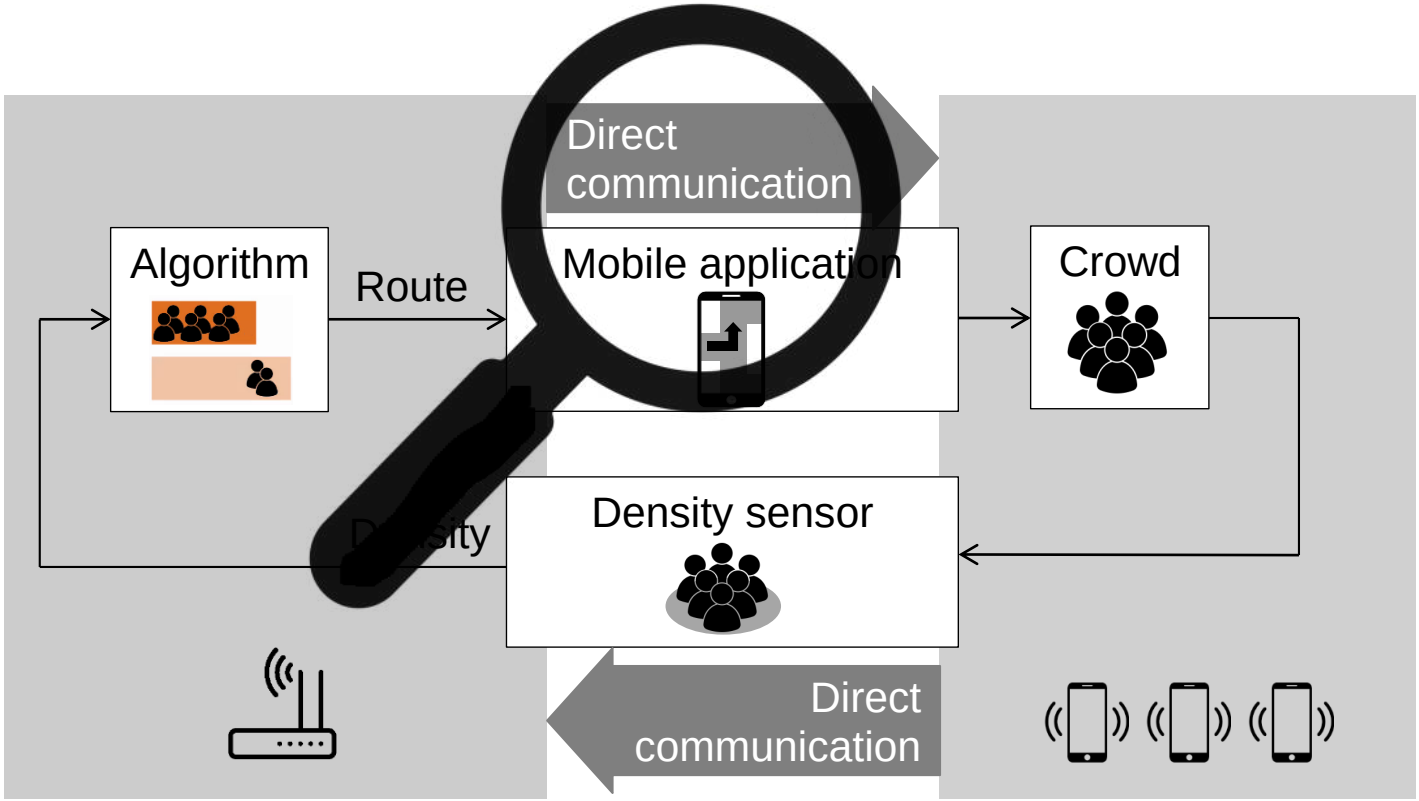


A density-based algorithm succesfully resolves congestion

Detailed comparison of algorithms:
See my publication “Guiding …” [6]



Does the information dissemination work?



Testing direct communication under worst case conditions

Simple technology

WLAN

IEEE 802.11p [2]

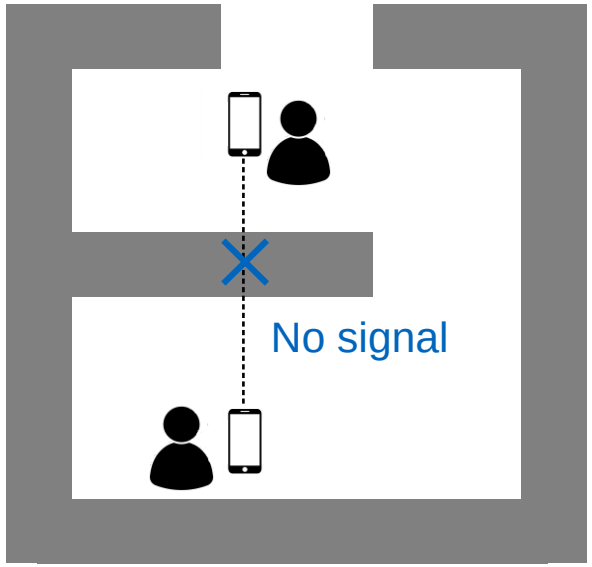
IEEE 802.11bd [14]

Cellular

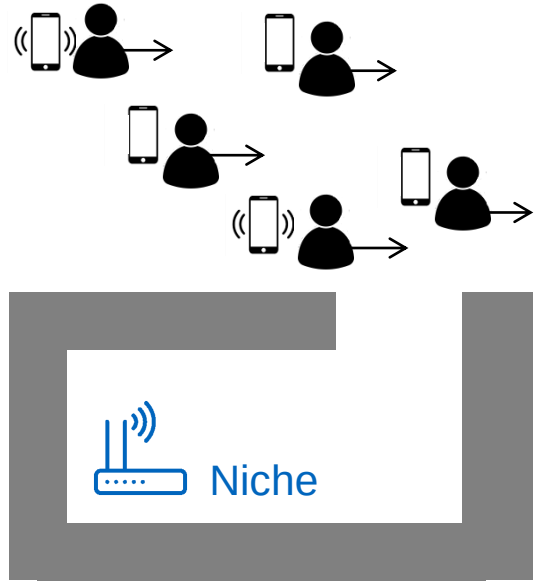
LTE V2X [15-19]

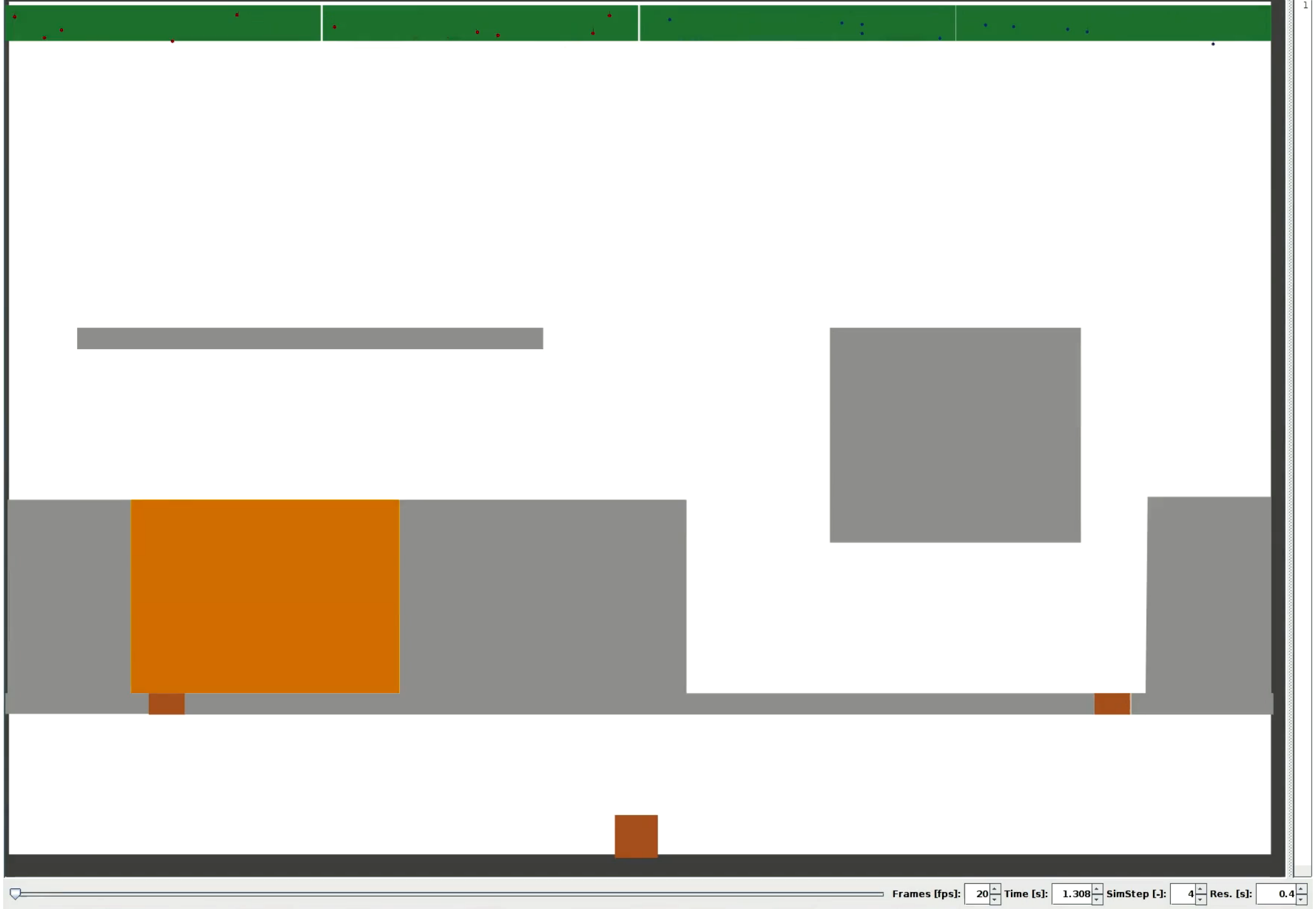
5G V2X [20-26]

Extreme signal modeling

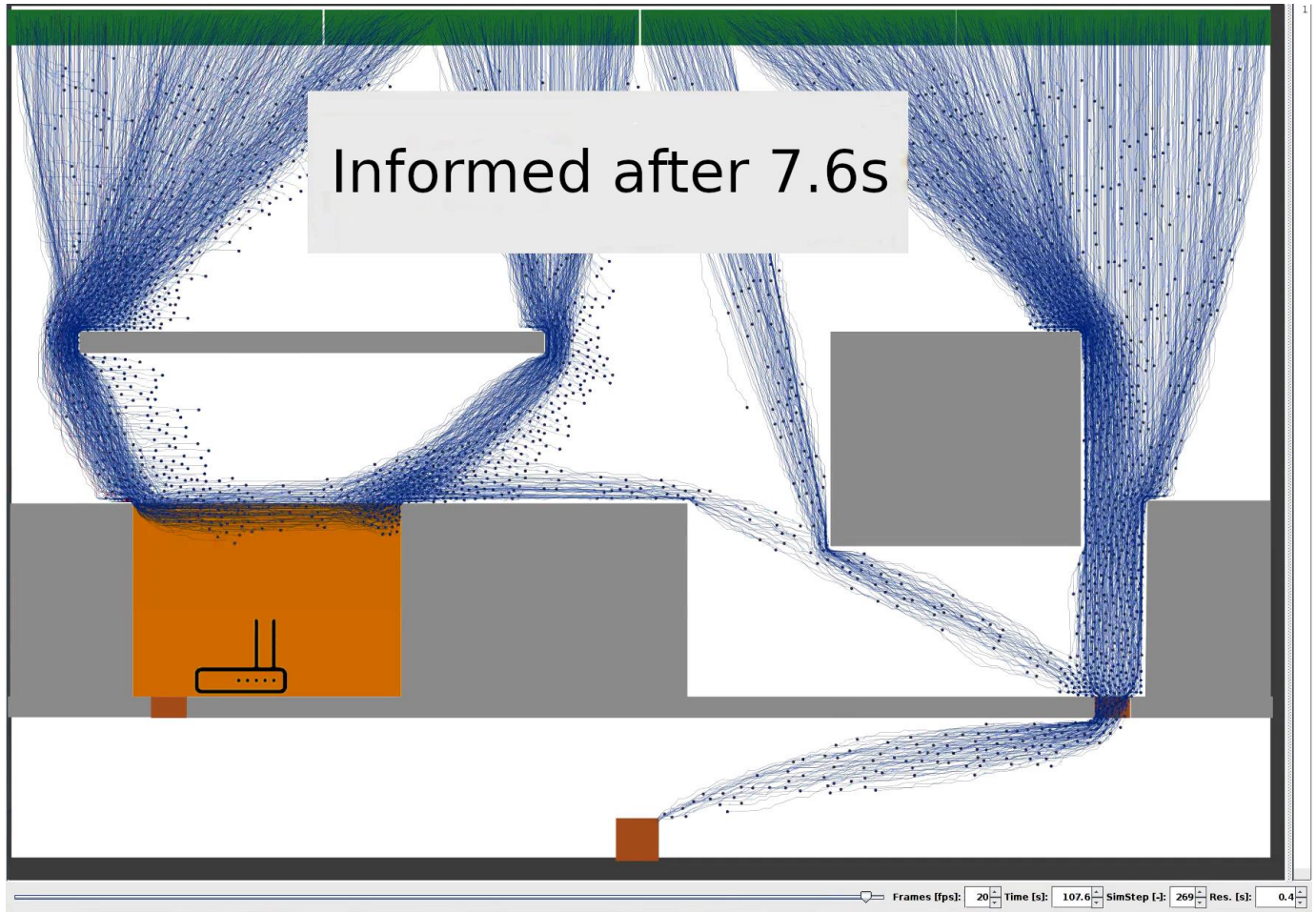


Scenario




Frames [fps]: 20
Time [s]: 1.308
SimStep [-]: 4
Res. [s]: 0.4

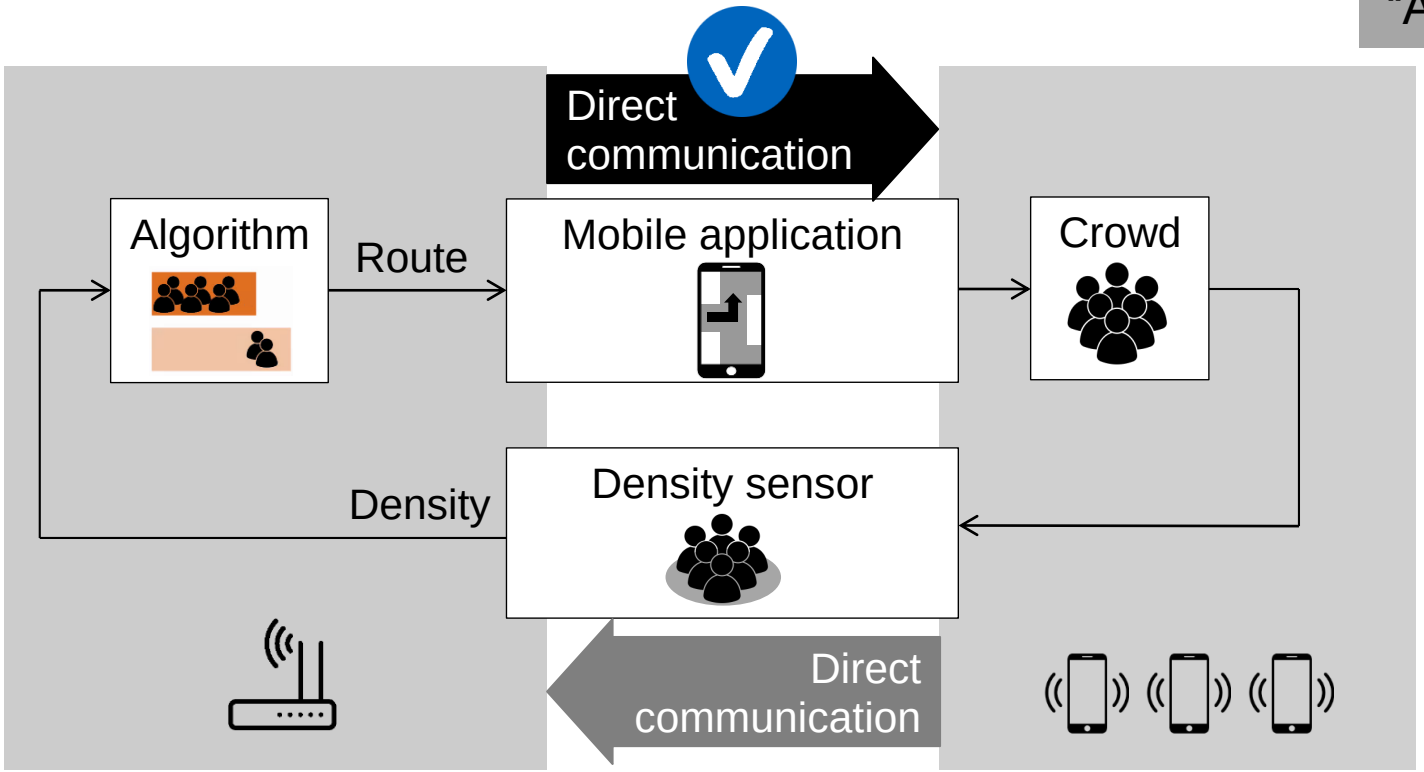
The crowd is successfully informed after several seconds



Parameter studies:
See my publication
“Analysis of info …” [27]

Direct communication is suitable for redirecting crowds

Parameter studies:
See my publication
“Analysis of info …” [27]



How to design mobile messages to foster compliance?

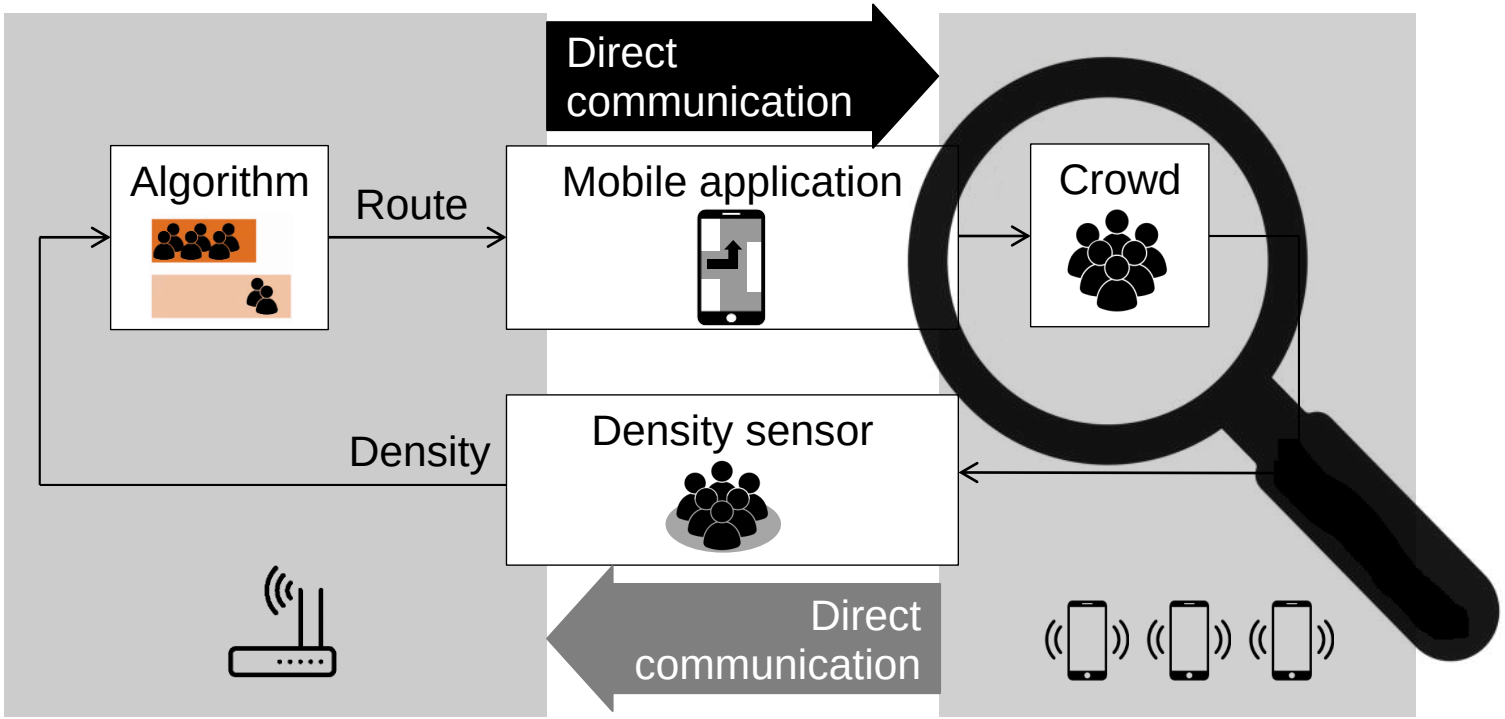
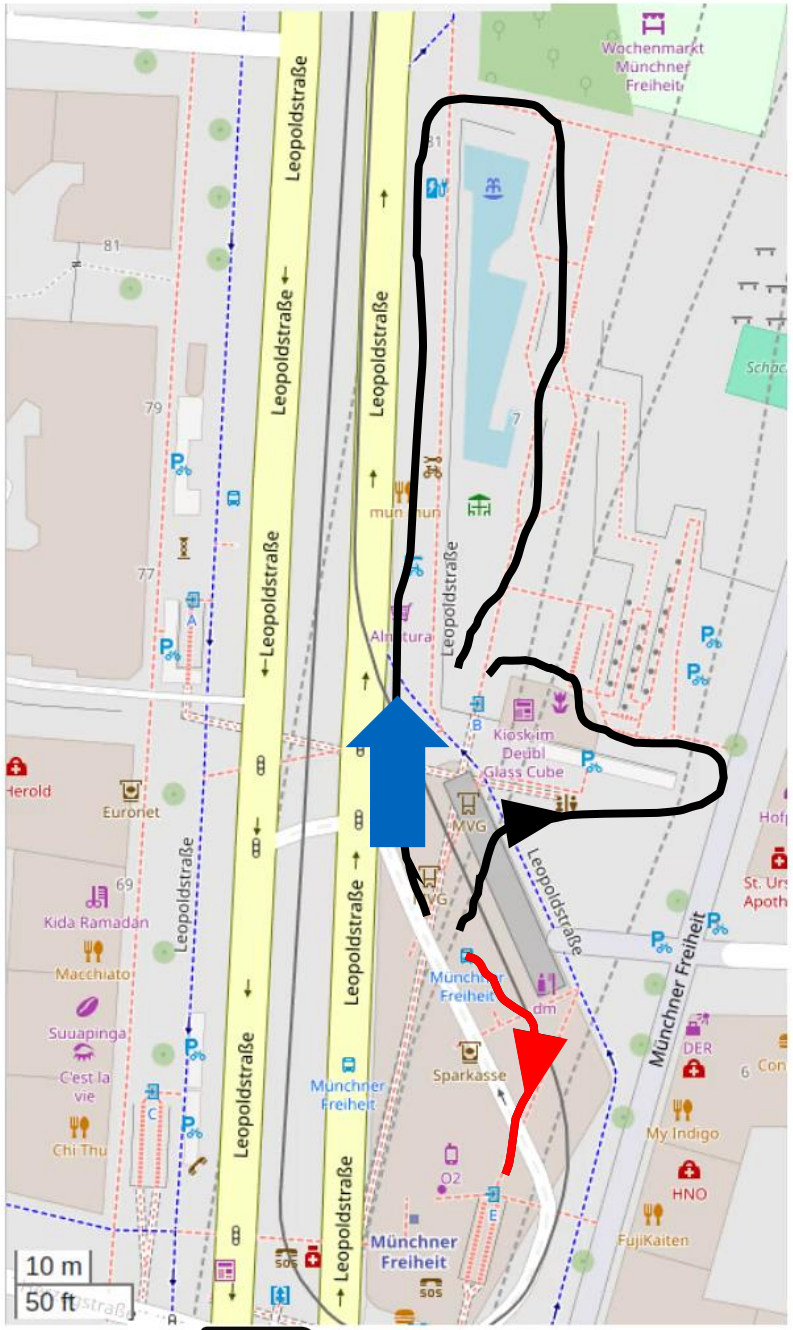


Image: Wolfram Schlenker, rights granted



©OpenStreetMap
openstreetmap.org/copyright

Long route

Metro station (surface level)
Münchner Freiheit
Munich, Germany

Medium route

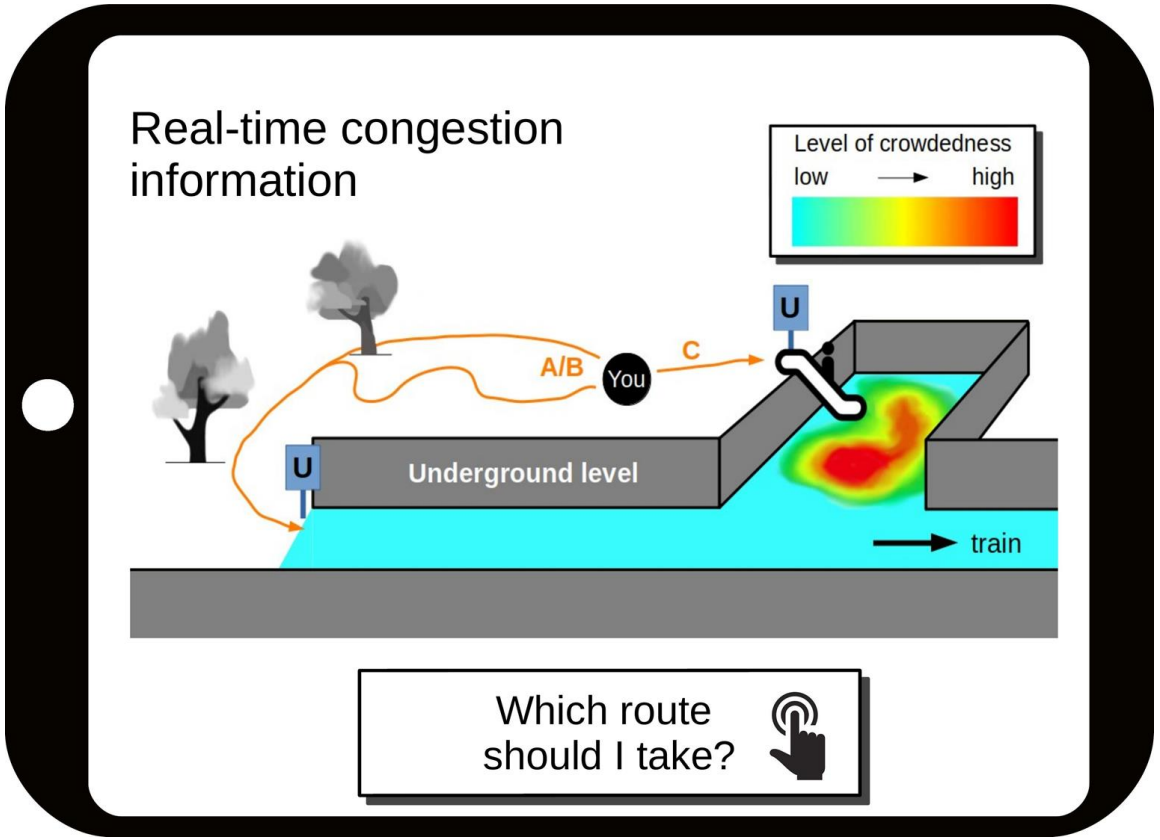
Short route

Online survey [28]: testing the effect of three message elements

Top-down view

Appeal to fans' team spirit

Congestion information

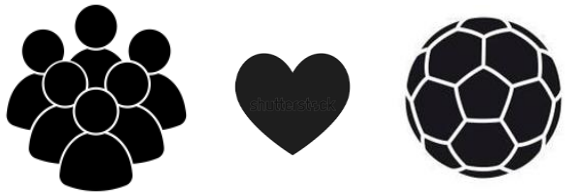


Online survey [28]: design of the survey

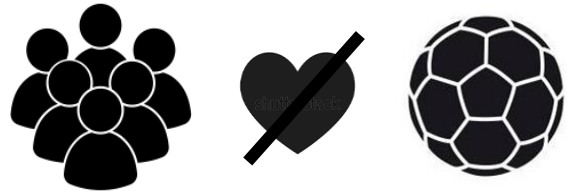
The combination of the three elements leads to 8 message designs:

Assumption: fans share a social identity (the control group does not)

Fans 921 participants

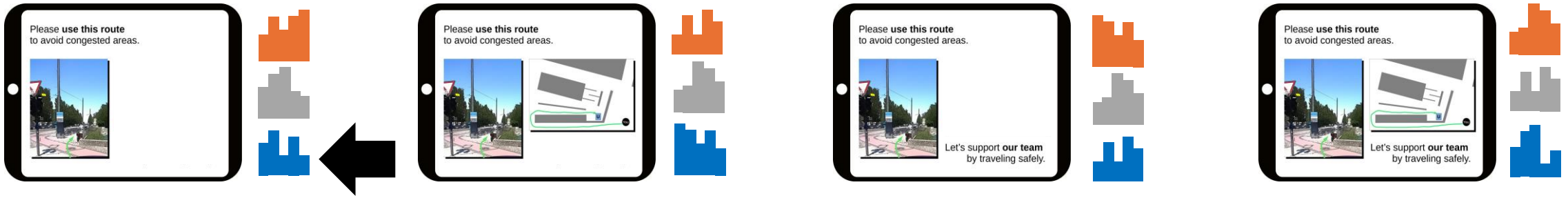


Control 444 participants

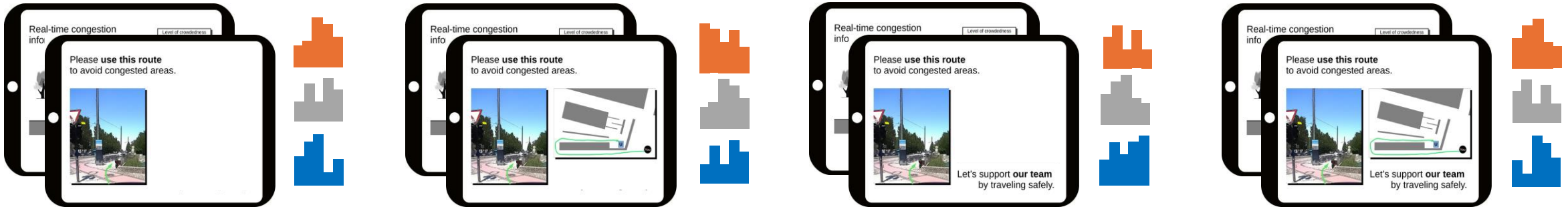


“How likely is it that you take the short, medium and long route?”

Participants rated the attractiveness of the short (●), medium (●), and long (●) route (5-point Likert scale)



Kruskal-Wallis test

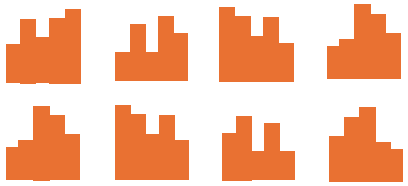


There are differences in between message designs

Results of Kruskal-Wallis tests:

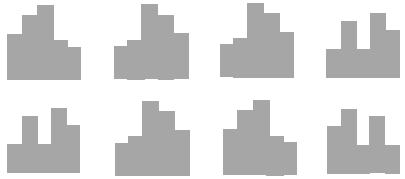
Fans:

Short route



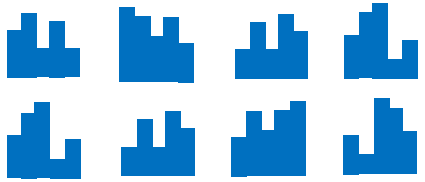
Significant difference ($p < 0.05$)

Medium route



Significant difference ($p < 0.05$)

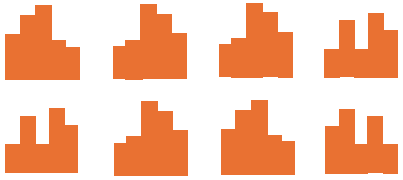
Long route



Significant difference ($p < 0.05$)

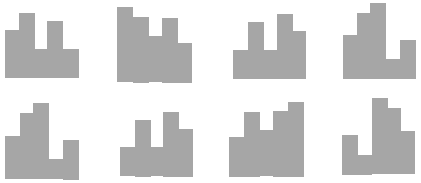
Control:

Short route



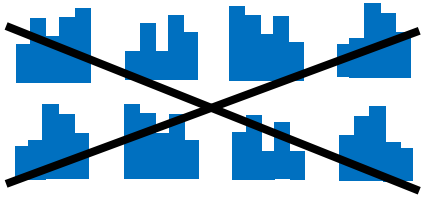
Significant difference ($p < 0.05$)

Medium route



Significant difference ($p < 0.05$)

Long route



Appealing to fans' "team spirit" can foster compliance

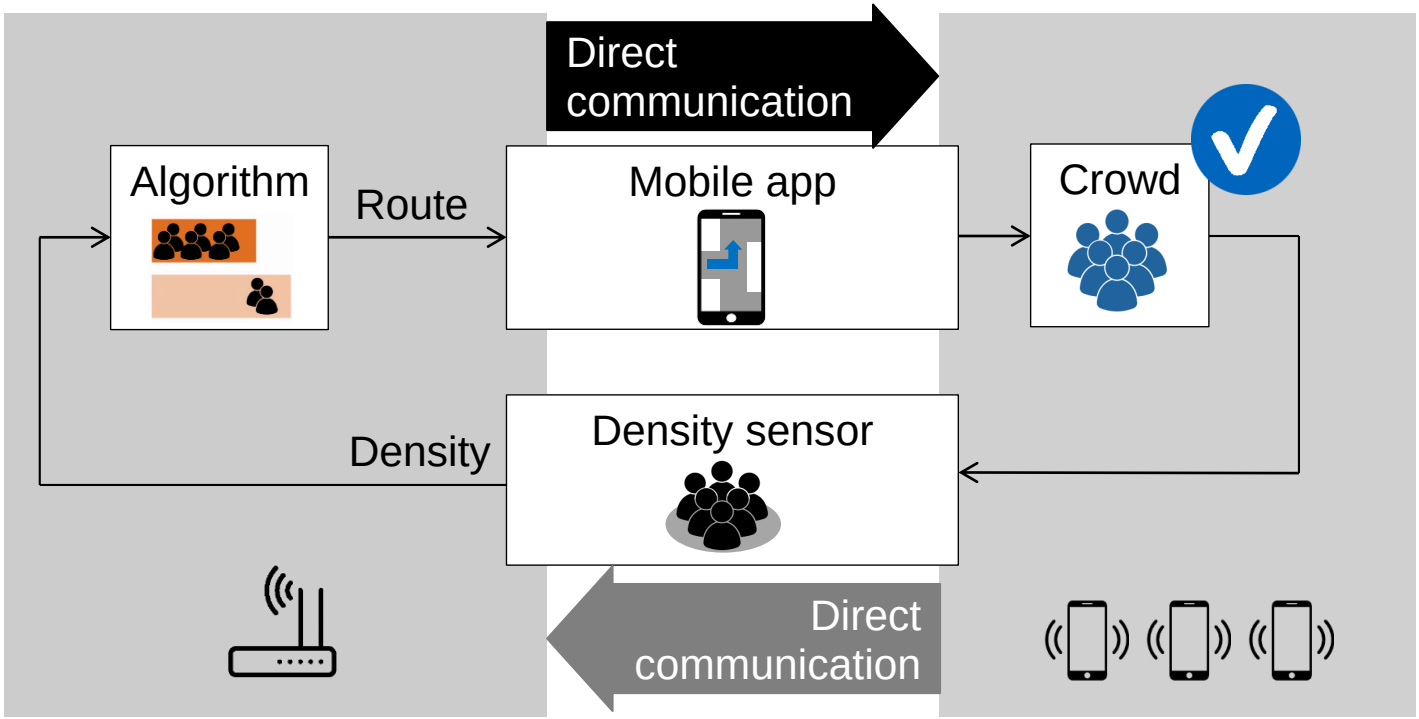
Fans:

Analysis of all combinations:
See my publication "Designing …" [28]

Adding "team spirit" made the long route more attractive in one combination [27].

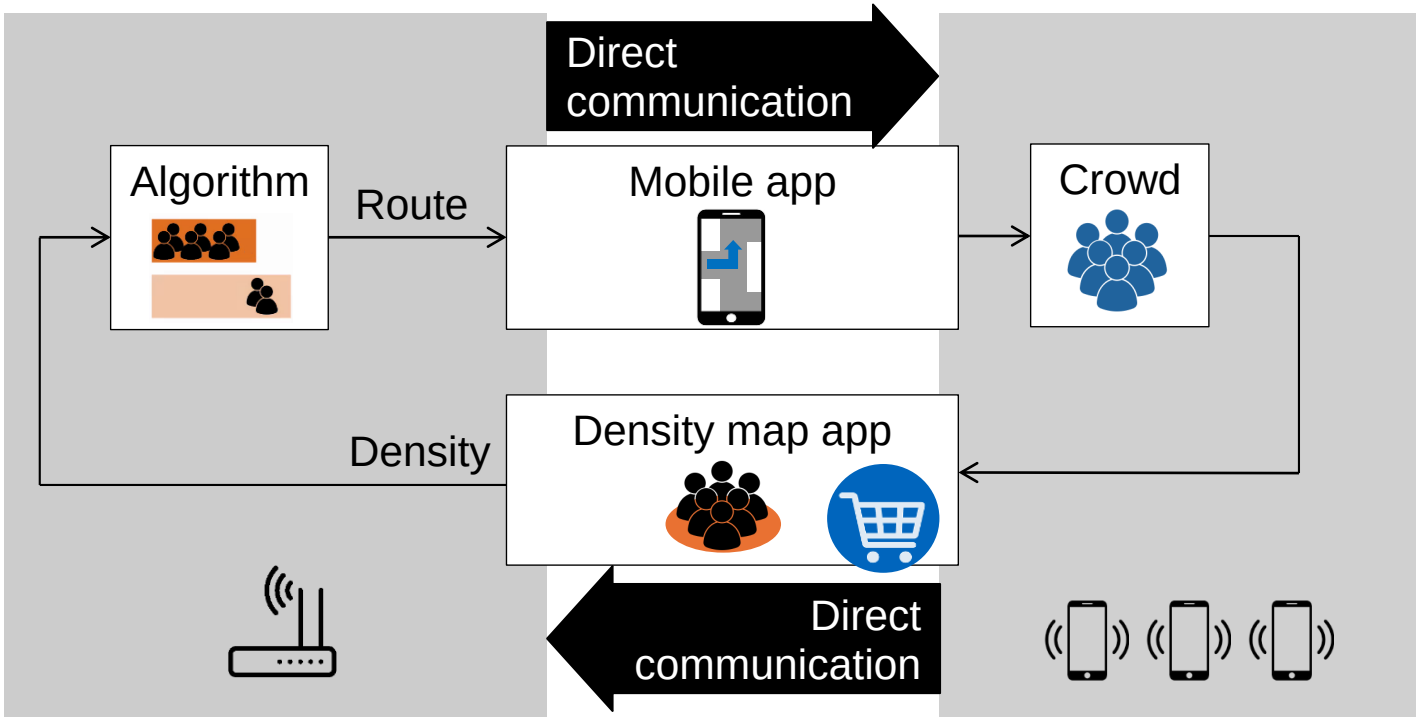
There is no ideal message design

Additional result from the survey:
Realistic route choice probabilities
See my publication “Designing …” [28]



Measuring densities using direct communication

I use the decentralized density map application (LTE sidelink, controlled mode) [28]:



Can the proposed system resolve safety-critical congestion?

I model, implement and simulate the overall system in CrowNet:

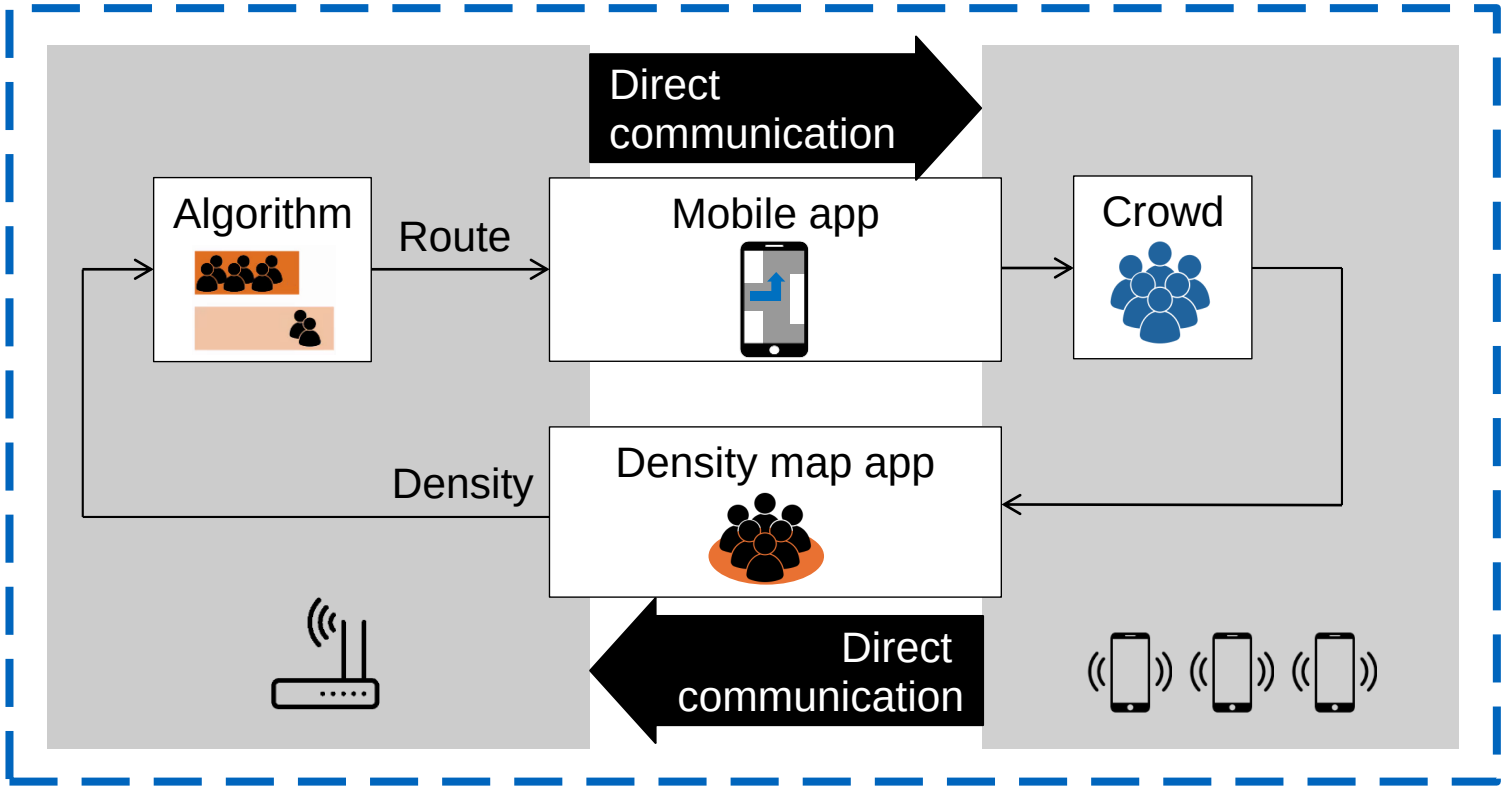
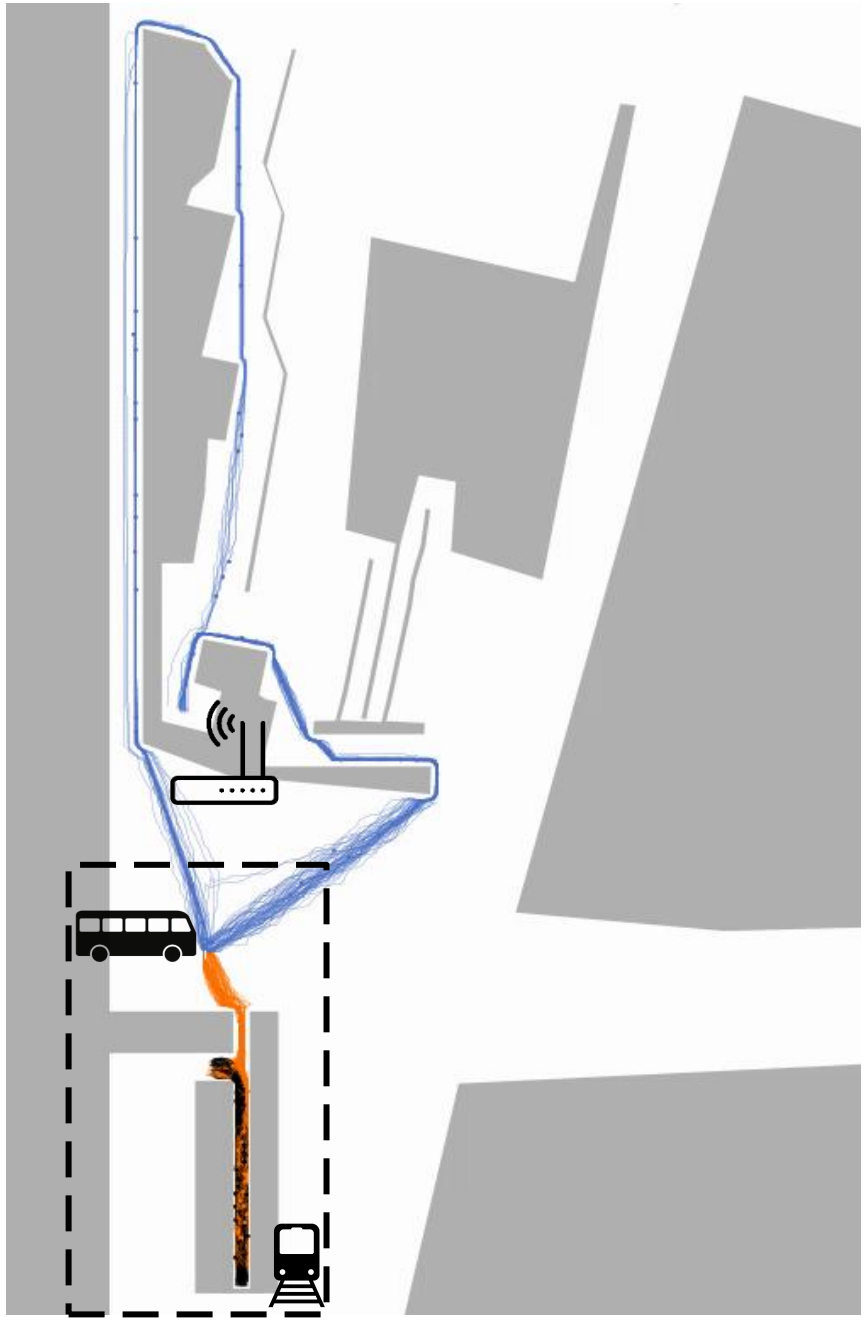
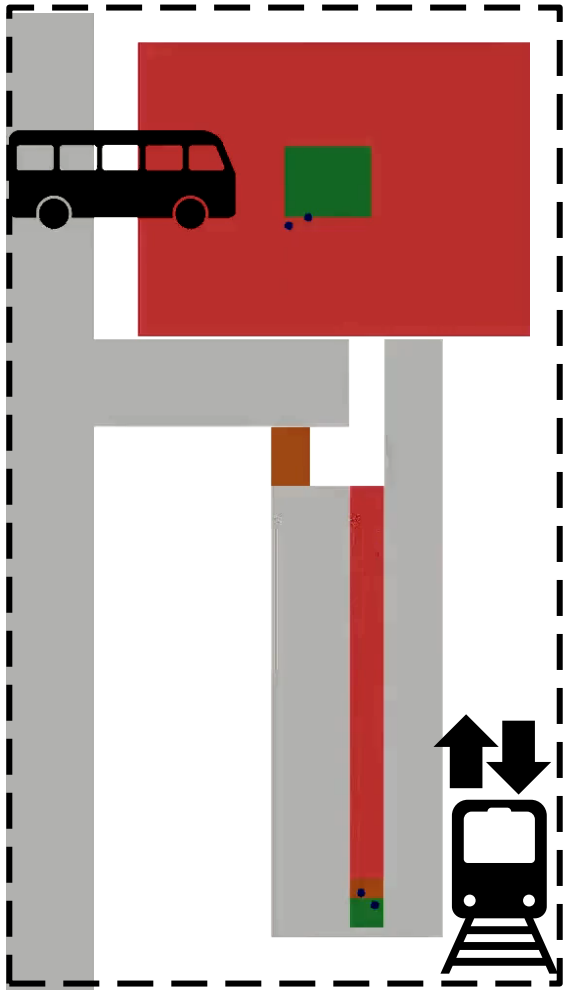


Image: Wolfram Schlenker, rights granted

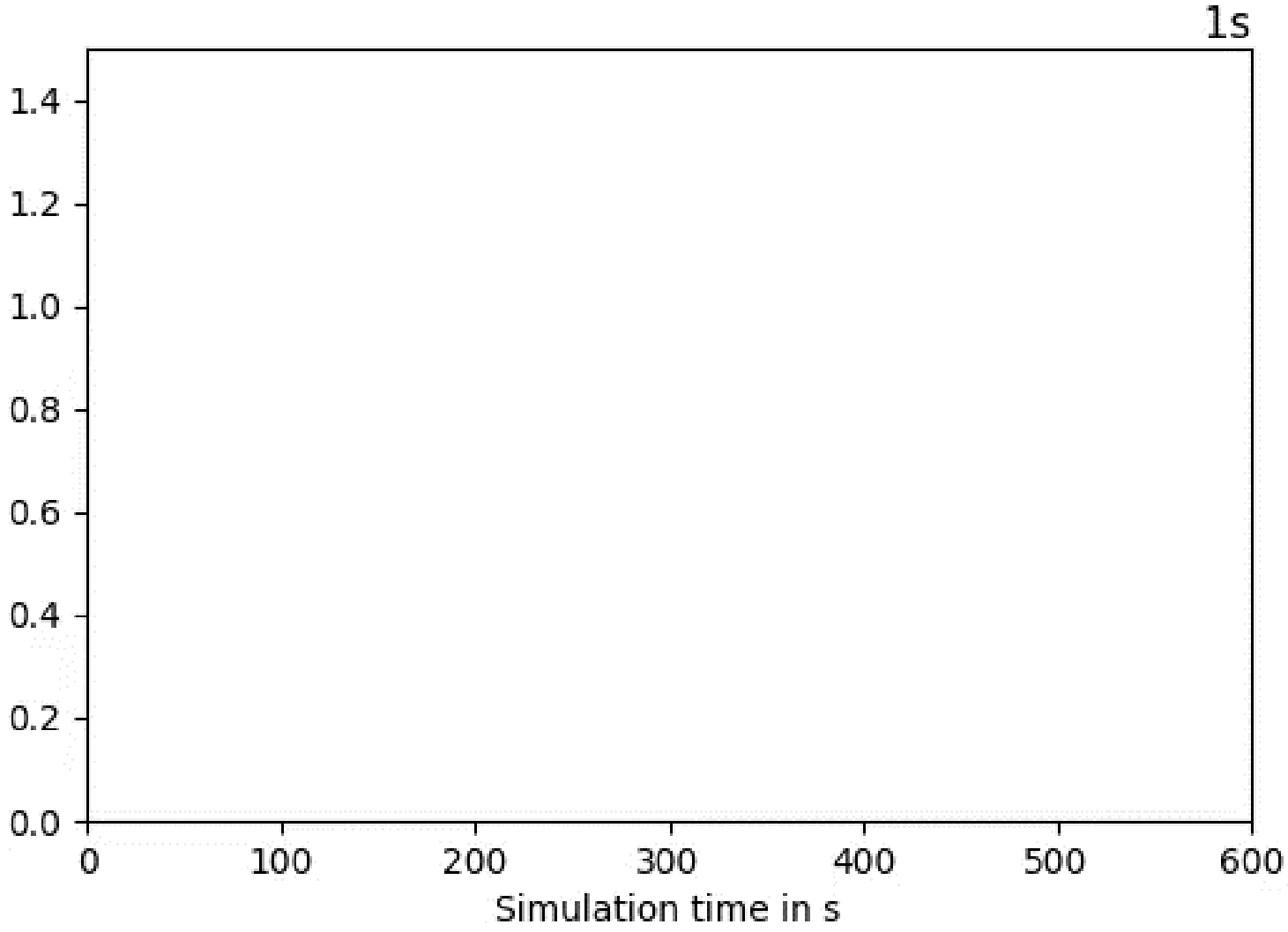


Crowd simulation
Münchner Freiheit
Munich, Germany

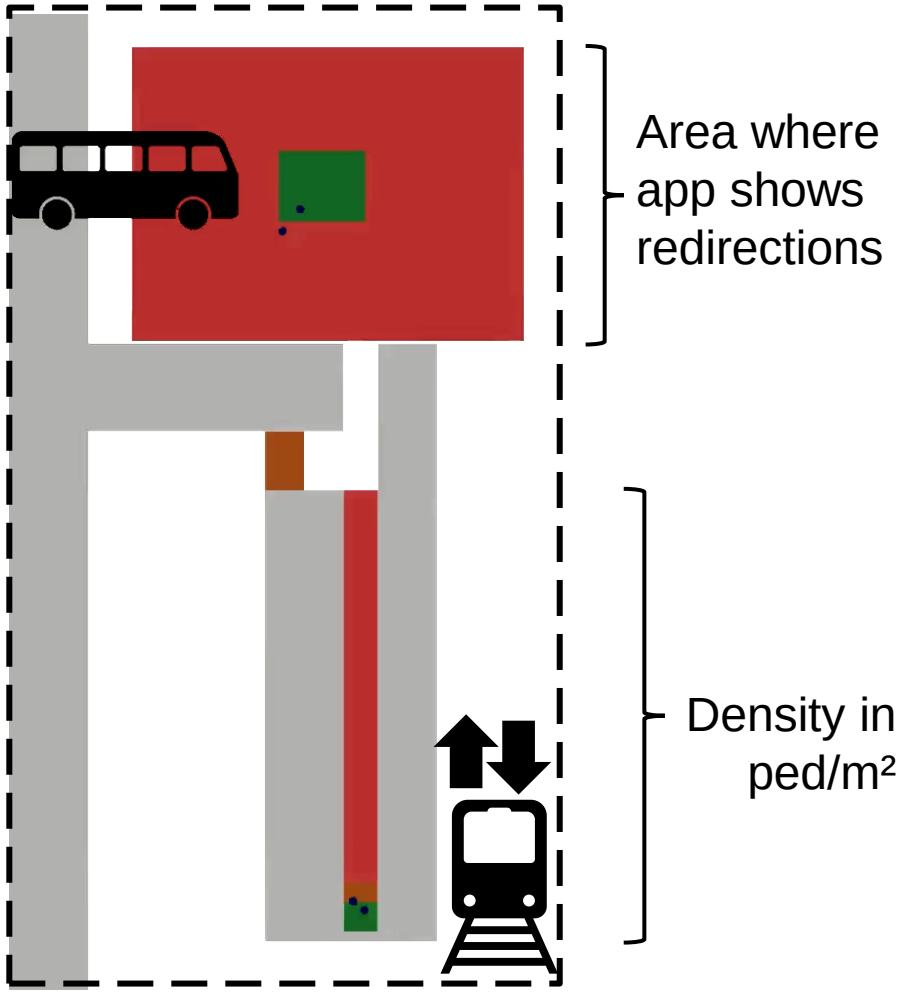
Without guidance: congestion along the short route

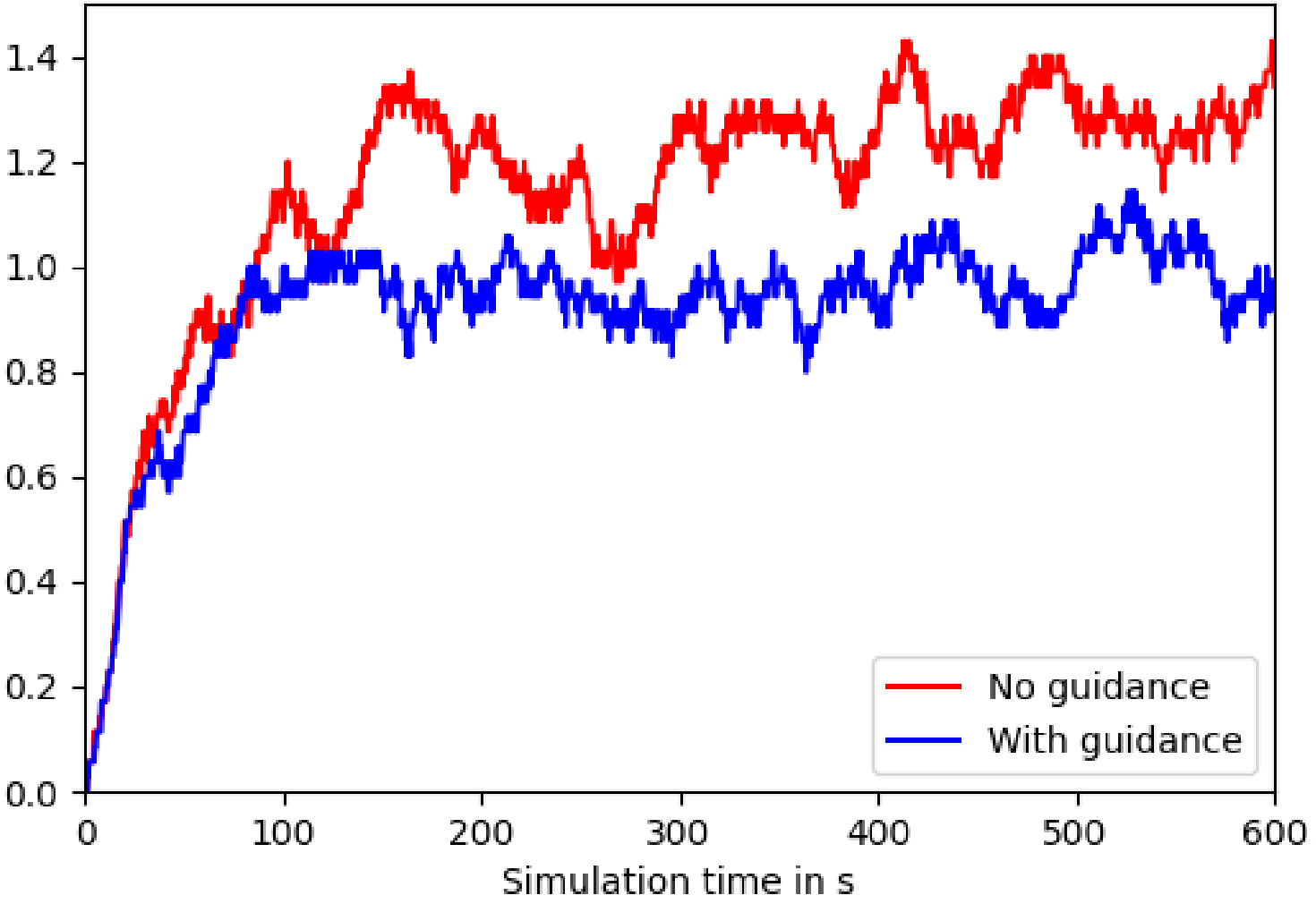


Density in ped/m²

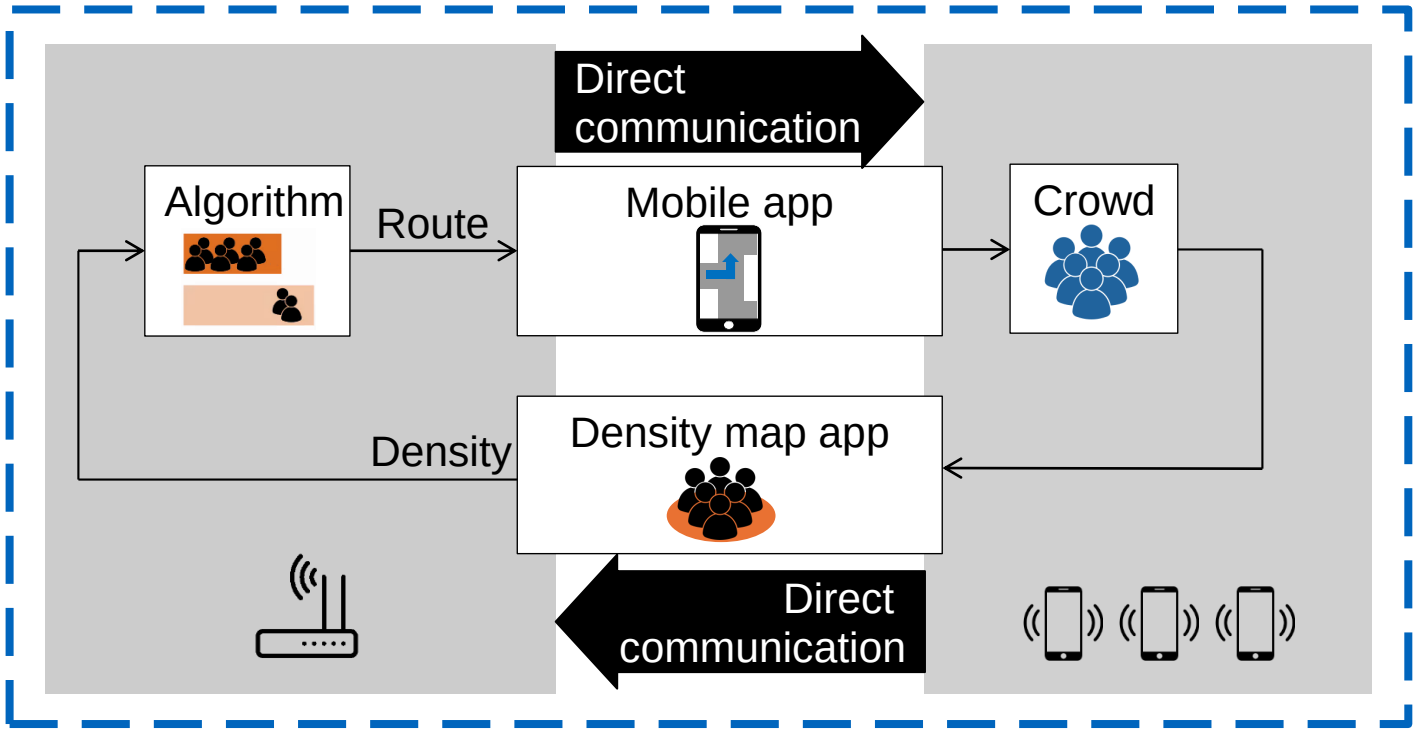


The guidance system resolves safety-critical congestion

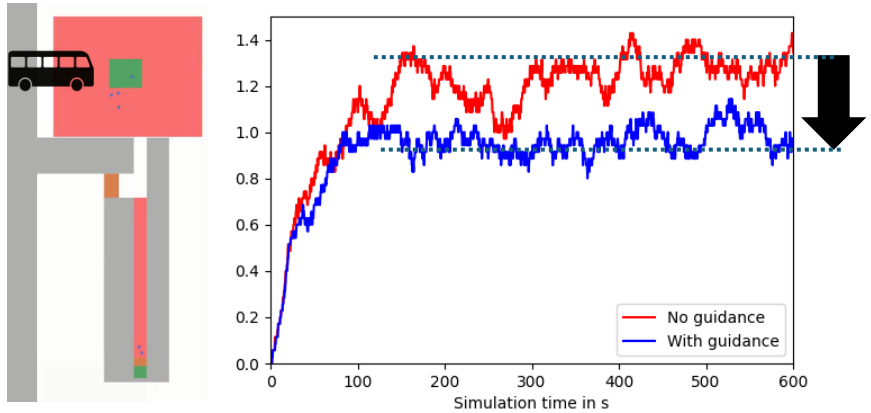




How can crowds be redirected with mobile applications based on direct communication technology?



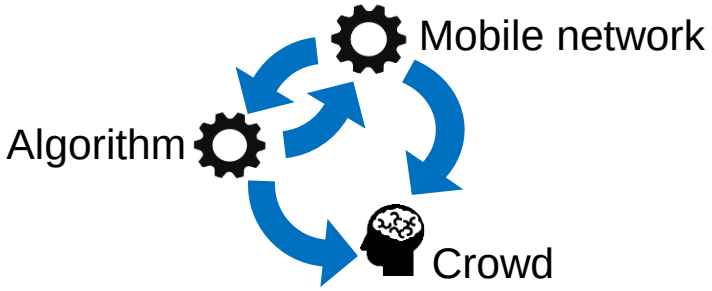
Proof of concept:



The system resolves safety-critical congestion.

I modeled and simulated a novel crowd guidance system

Novel socio-technical system

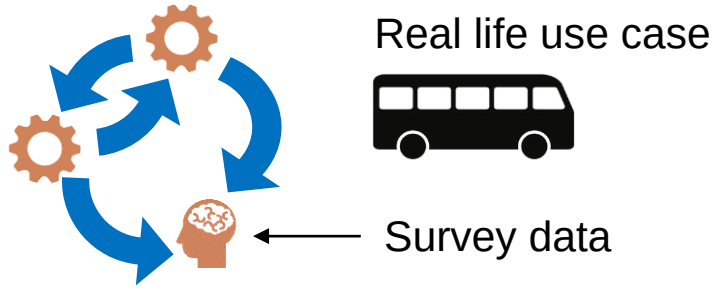


Multi-method investigation

- Algorithm
  Modeling & Simulation
- Direct communication
  Modeling & Simulation
- Crowd behavior
  Survey

See my publications [6,27,28]

Proof of concept

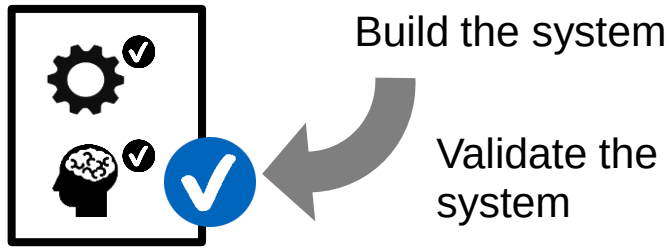


The system resolves congestion

Novel simulator CrowNet

github.com/roVer-HM/crownet

Next step

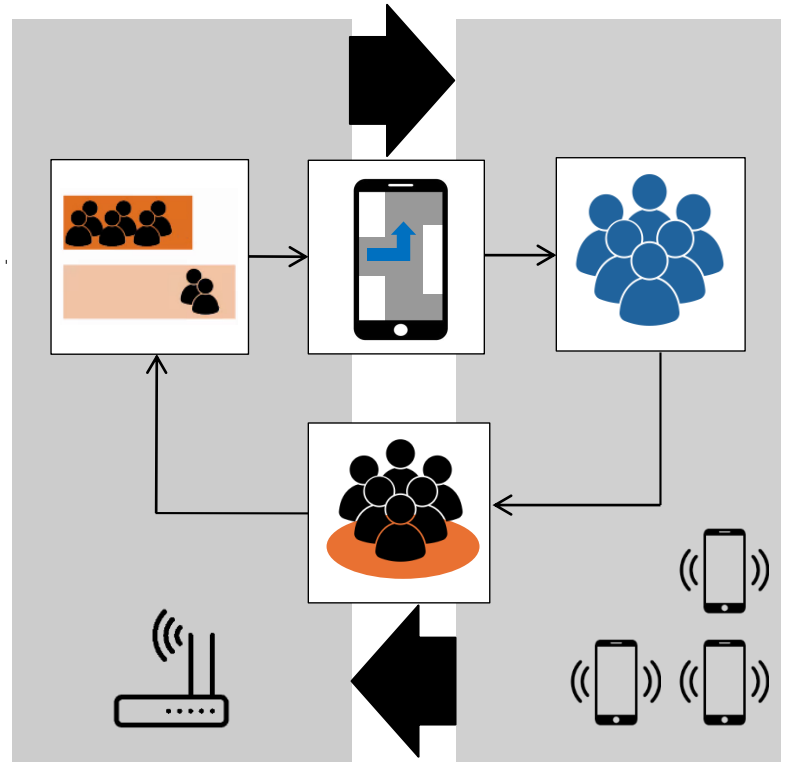


Conclusion

A system was proposed that detects and redirects crowds through mobile applications.

It is possible to redirect crowds using mobile applications based on direct communication technology.

The proposed system can resolve safety-critical jams even when only a part of the crowd uses the technology.



References (1/2)

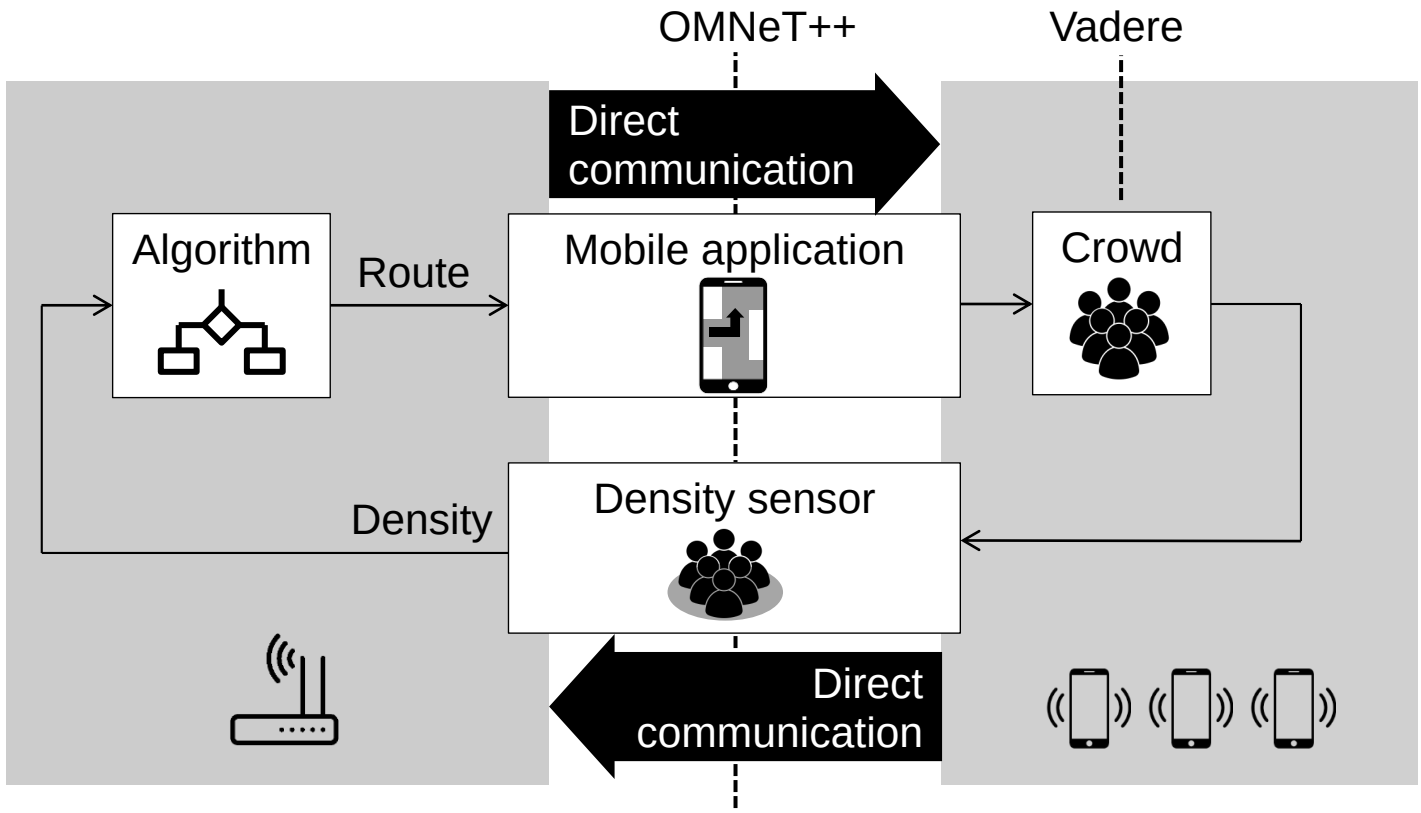
(1) Claudio Feliciani, Kenichiro Shimura, and Katsuhiro Nishinari. Introduction to Crowd Management. Managing Crowds in the Digital Era: Theory and Practice. 1st ed. Springer Cham, 2021. doi: 10.1007/978-3-030-90012-0.
(2) 802.11 WG Wireless LAN Working Group. IEEE 802.11p-2010. Tech. rep. IEEE standards association, 2010.
(3) Stefan Schuhbäck et al. Towards a Bidirectional Coupling of Pedestrian Dynamics and Mobile Communication Simulation. In: Proceedings of the OMNeT++ Community Summit 2019. 2019. doi: 10.29007/nnfj.
(4) Benedikt Kleinmeier, Benedikt Zönnchen, Marion Gödel, Gerta Köster. Vadere: An open-source simulation framework to promote interdisciplinary understanding. In: Collective Dynamics (4). 2019. doi: 10.17815/CD.2019.21
(5) Antonio Virdis, Michael Kirsche (eds). Recent Advances in Network Simulation. Springer Pub. 2019. doi:10.1007/978-3-030-12842-5
(6) Christina Maria Mayr and Gerta Köster. Guiding crowds when facing limited compliance: Simulating strategies. In: PLOS ONE 17.11 (Nov. 2022), pp. 1-24. doi: 10.1371/journal.pone.0276229.
(7) H. Ren, Y. Yan, and F. Gao. Variable guiding strategies in multi-exits evacuation: Pursuing balanced pedestrian densities. In: Applied Mathematics and Computation 397 (2021). doi: 10.1016/j.amc.2021.125965.
(8) F. Gao et al. Effect of density control in partially observable asymmetric-exit evacuation under guidance: Strategic suggestion under time delay. In: AppliedMathematics and Computation 418 (2022). doi: 10.1016/j.amc.2021.126838.
(9) Pushkin Kachroo et al. Pedestrian Dynamics: Feedback Control of Crowd Evacuation. Springer, 2010. doi: 10.1007/978-3-540-75561-6.
(10) Apoorva Shende, Mahendra Singh, and Pushkin Kachroo. Optimization-Based Feedback Control for Pedestrian Evacuation From an Exit Corridor. In: IEEE Transactions on Intelligent Transportation Systems 12 (Dec. 2011), pp. 1167-1176. doi: 10.1109/TITS.2011.2146251.
(11) Apoorva Shende, Mahendra P. Singh, and Pushkin Kachroo. Optimal Feedback Flow Rates for Pedestrian Evacuation in a Network of Corridors. In: IEEE Transactions on Intelligent Transportation Systems 14.3 (2013), pp. 1053-1066. doi: 10.1109/TITS.2013.2250965.
(12) Zhe Zhang, Limin Jia, and Yong Qin. “Level-of-Service Based Hierarchical Feedback Control Method of Network-Wide Pedestrian Flow”. In: Mathematical Problems in Engineering 2016 (Jan. 2016), pp. 1-4. doi: 10.1155/2016/9617890.
(13) Marcel Menner et al. MPC-based Pedestrian Routing for Congestion Balancing. Mitsubishi Electric Research Laboratories, 2023.
(14) 802.11 WG Wireless LAN Working Group. IEEE 802.11bd-2022 - IEEE Standard for Information Technology -Telecommunications and Information Exchange between Systems Local and Metropolitan Area Networks - Specific Requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY). Specifications Amendment 5: Enhancements for Next Generation V2X. Tech. rep. Mar. 10, 2023.

References (2/2)

(15) 3GPP Technical Specification Group Services and System Aspects. TR 22.885 Study on LTE Support for Vehicle to Everything (V2X) Services (Release 14). Tech. rep. 2015.
(16) 3GPP Technical Specification Group Services and System Aspects. TR 36.885 Study on LTE-Based V2X Services (Release 14). Tech. rep. 2016.
(17) 3GPP Technical Specification Group Services and System Aspects. 3GPP TS 22.185 Service Requirements for V2X Services (Release 16). Tech. rep. 2020.
(18) 3GPP Technical Specification Group Services and System Aspects. TS 23.285 Architecture Enhancements for V2X Services (Release 16). Tech. rep. 2020
(19) 3GPP Technical Specification Group Radio Access Network. TS 36.213 Evolved Universal Terrestrial Radio Access (E-UTRA); Physical Layer Procedures (Release 16). Tech. rep. 2020.
(20) 3GPP Technical Specification Group Services and System Aspects. TR 22.886 Study on Enhancement of 3GPP Support for 5G V2X Services (Release 16). Tech. rep. 2018.
(21) 3GPP Technical Specification Group Radio Access Network. TR 38.885 Study on NR Vehicle-to-Everything (V2X) (Release 16). Tech. rep. 2019.
(22) 3GPP Technical Specification Group Services and System Aspects. TS 23.287 Architecture Enhancements for 5G System (5GS) to Support Vehicle-to-Everything (V2X) Services (Release 16). Tech. rep. 2020.
(23) 3GPP Technical Specification Group Services and System Aspects. TS 22.186 Enhancement of 3GPP support for V2X scenarios (Release 16). Tech. rep. 2019.
(24) 3GPP Technical Specification Group Radio Access Network. TS 38.213 Physical Layer Procedures for Control (Release 16). Tech. rep. 2020.
(25) 3GPP Technical Specification Group Radio Access Network. TS 38.321 Medium Access Control (MAC) Protocol Specification (Release 16). Tech. rep. 2020.
(26) 3GPP Technical Specification Group Radio Access Network. TS 37.895 Overall Description of Radio Access Network (RAN) Aspects for Vehicle-to-Everything (V2X) Based on LTE and NR (Release 16). Tech. rep. 2020.
(27) Christina Maria Mayr, Stefan Schuhbäck, Lars Wischhof, Gerta Koster. Analysis of information dissemination through direct communication in a moving crowd. Safety Science (142) 105386. doi: 10.1016/j.ssci.2021.105386
(28) Christina Maria Mayr, Anne Templeton, and Gerta Köster. Designing mobile application messages to impact route choice: A survey and simulation study. In: PLOS ONE 18.4 (Apr. 2023), pp. 1–20. doi: 10.1371/journal.pone.0284540.
(29) Stefan Schuhbäck, Lars Wischhof, and Jörg Ott. Cellular Sidelink Enabled Decentralized Pedestrian Sensing. In: IEEE Access 11 (2023), pp. 13349-13369. doi: 10.1109/access.2023.3242946.
(30) Fernando Fonseca et al. Use and Perceptions of Pedestrian Navigation Apps: Findings from Bologna and Porto. In: ISPRS International Journal of Geo-Information 10.7 (2021). doi: 10.3390/ijgi10070446.

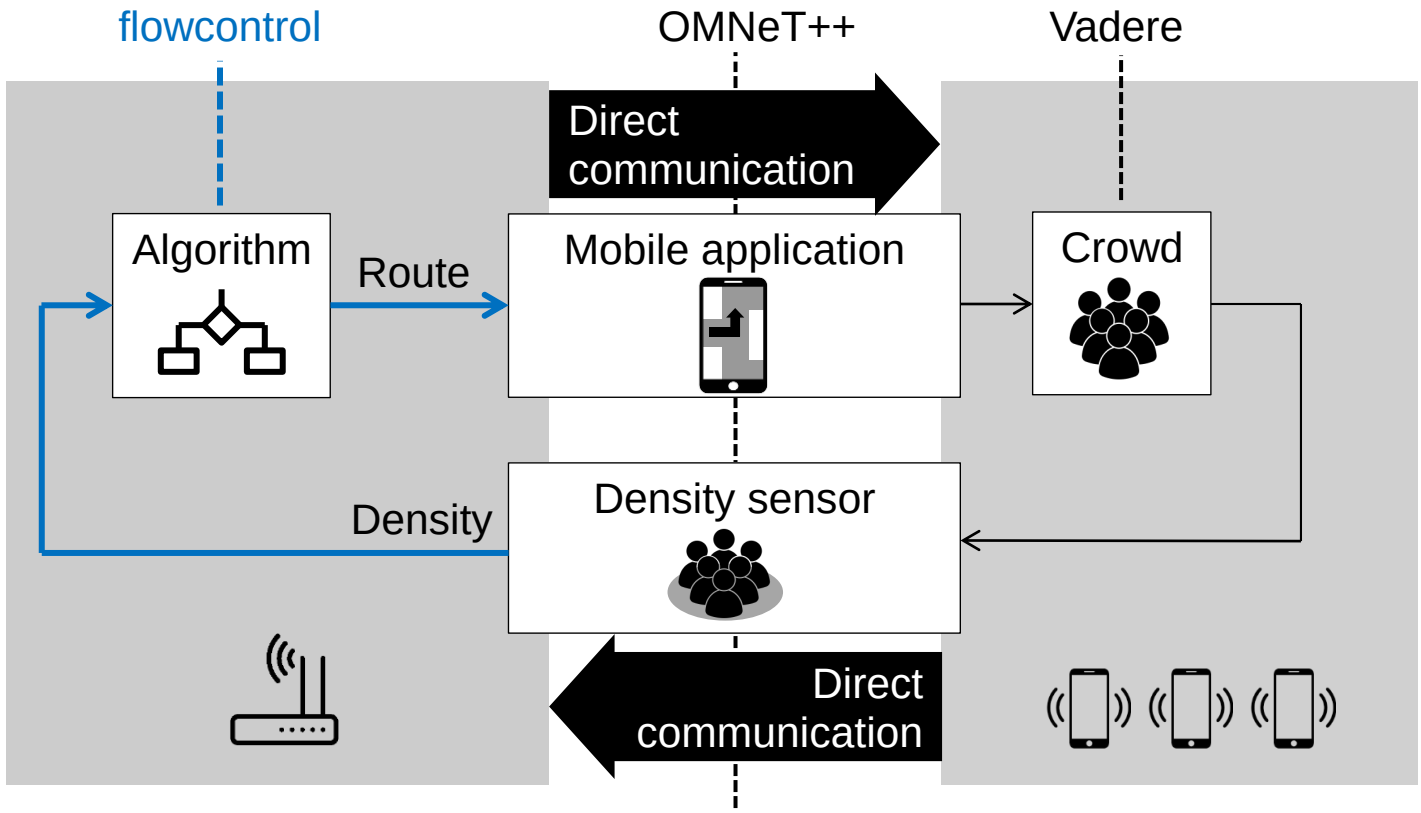
CrowNet: a novel simulation framework

Initial simulator coupling [3]: Vadere [4] and OMNeT++ [5]



My major contribution to CrowNet: flowcontrol

I developed flowcontrol [6] and integrated it:



Algorithm study

Alternative algorithm

Parameter settings:

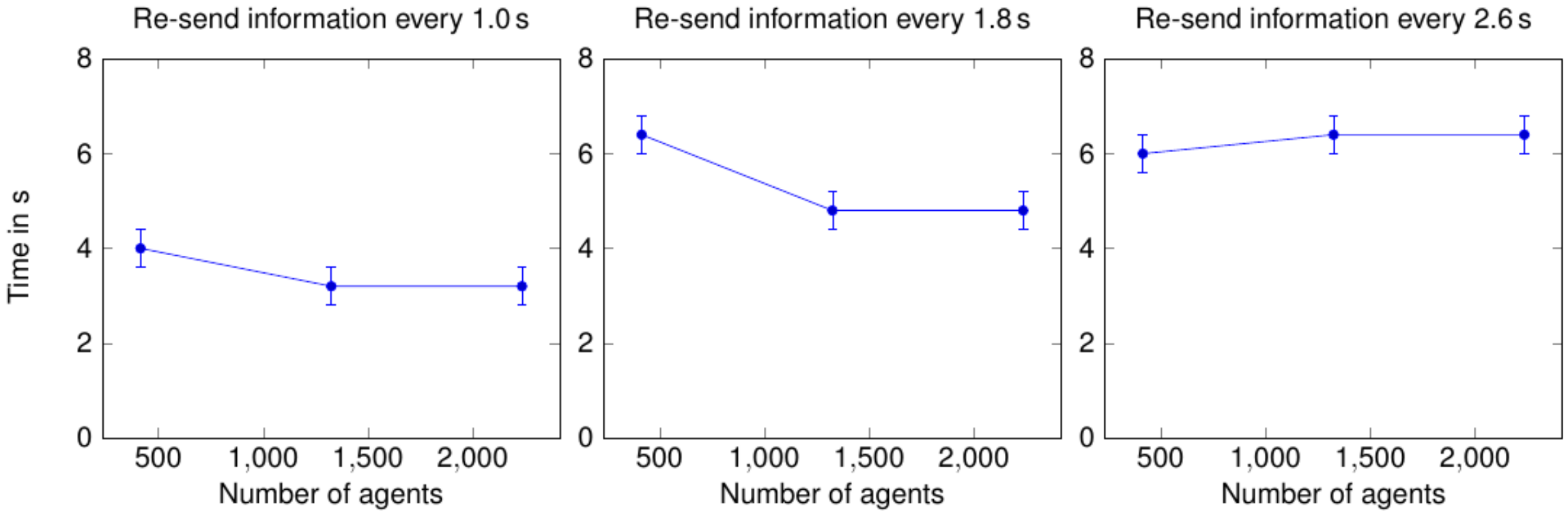
Route recommendation: every 2s

Corridor width = 2.5m

Inflow = 1.6ped/(ms) “8 agents every 2s” (=30*8ped/2.5m/60s) (4ped/s)

Information dissemination study

It takes several seconds to distribute the information.



Message design

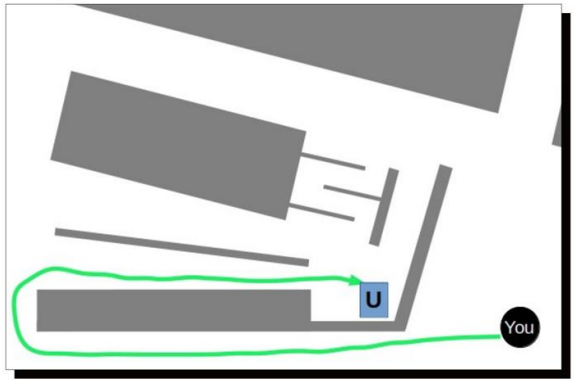
Dropout: 44.51%
Number of participants who completed the survey: 444 (control), 921 (fans)

Group	<18	18-25	26-35	36-50	51-65	>65	n
Fans	0 %	17 %	38 %	34 %	10 %	1 %	921
Students and faculty associates	7 %	43 %	28 %	8 %	11 %	3 %	444

Table 4.8.: Age distribution of the two groups: *football fans* (1), and *students and faculty associates* (2). *Students and faculty associates* were younger than fans which might be explained by the fact that most of them were students.

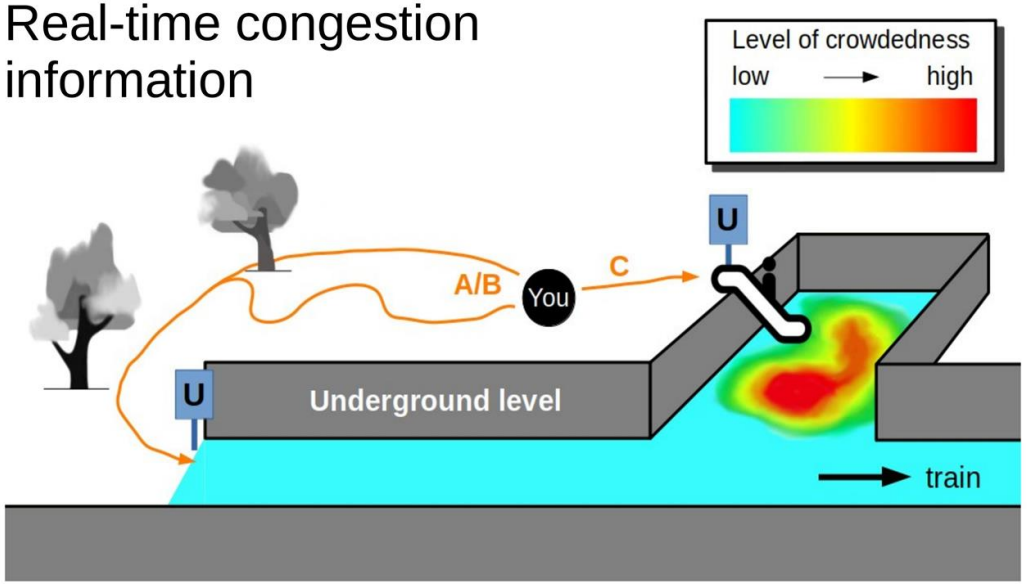
Message design study

Please **use this route**
to avoid congested areas.



Let's support **our team**
by traveling safely.

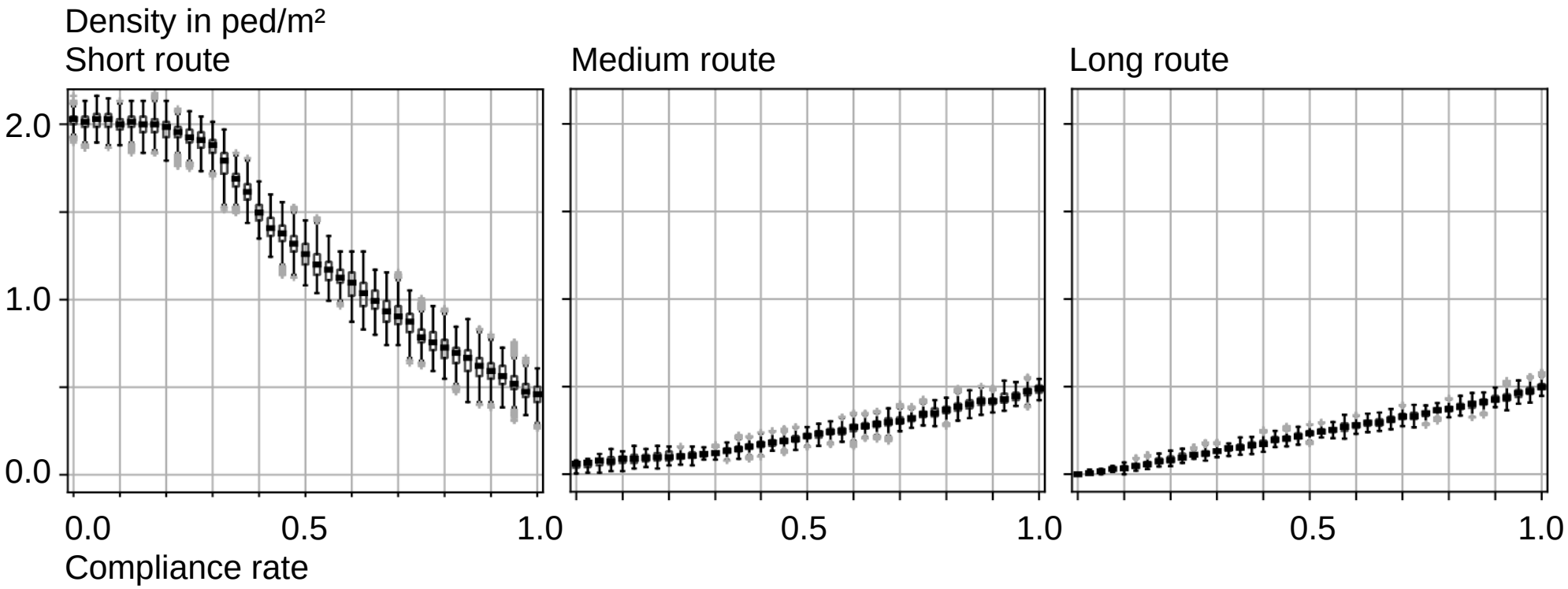
Real-time congestion information



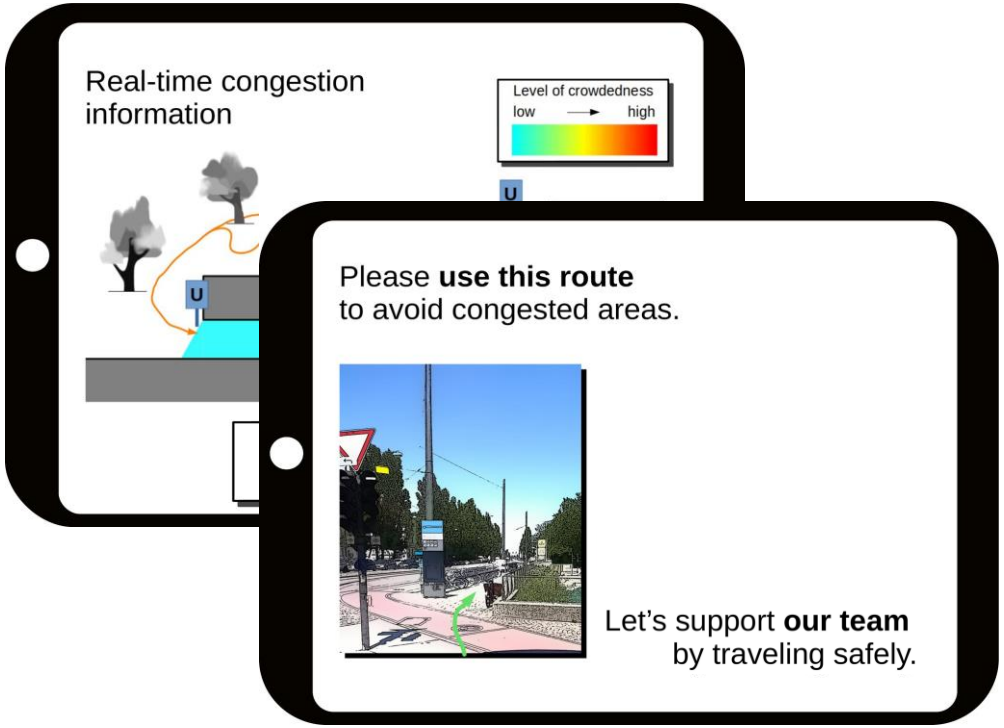
Which route should I take?

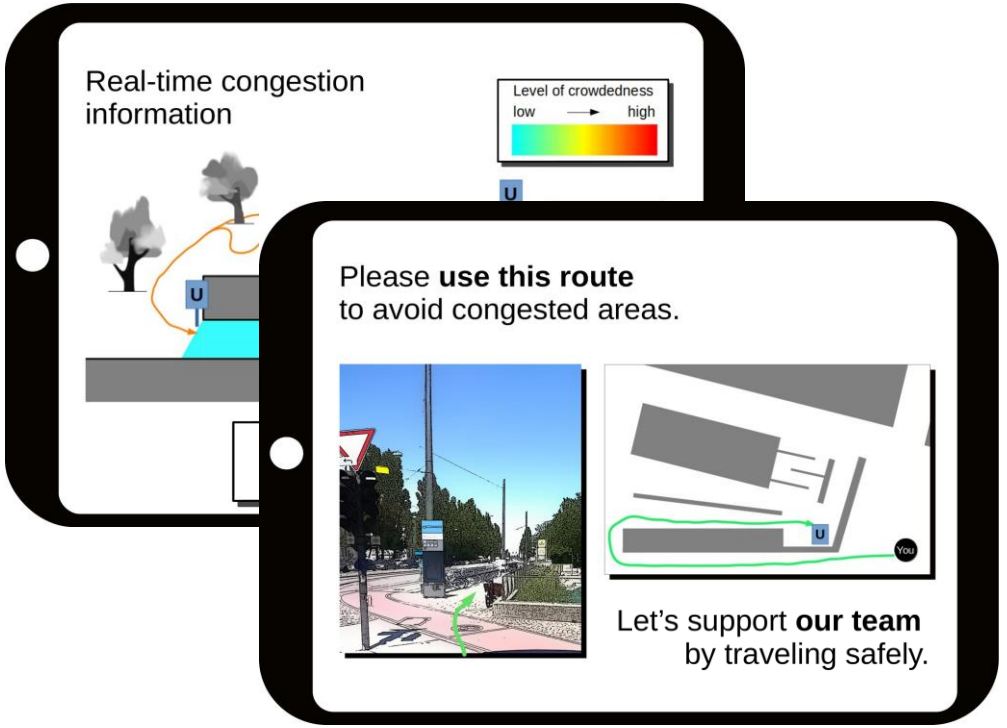
Algorithm study

Alternative algorithm



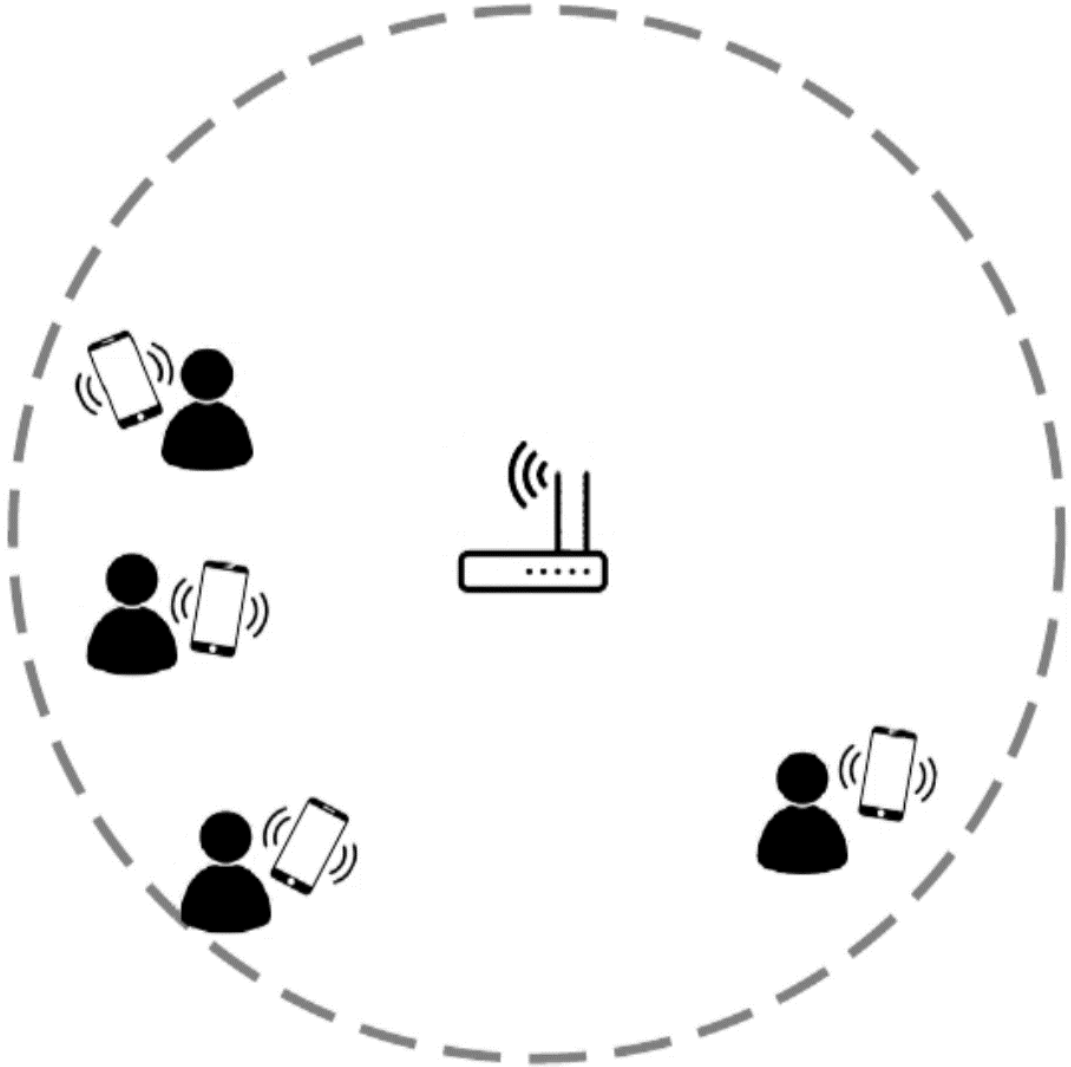
Can appeal to fans' "team spirit" foster compliance? (see [27])





Density map application

LTE sidelink communication



System test

Route recommendation: every 2s possible

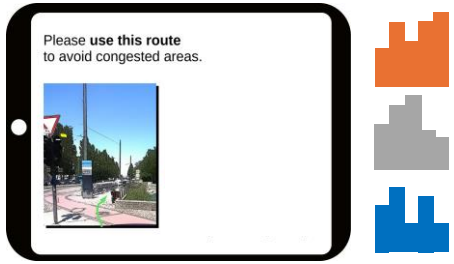
Short corridor: Corridor width = 1.75m

Inflows:
Bus arrivals: 60peds/min
Counterflow: 40peds/min

Route distributions without recommendations: 49% short, 30% medium, 22% long
Route distribution when the long route is recommended: 25% short, 35% medium, 40% long

Participants ranked the attractiveness of the 3 routes

5-point scale



Kruskal Wallis test

H_0: The mean ranks (~ “medians”) are equal across 3+ populations.

The smaller the p value, the more likely the null hypothesis must be rejected.
“ p < 0.05 “ -> reject H_O -> “The mean ranks are equal” is false -> difference
“ p >= 0.05 “ -> confirm H_O -> “The mean ranks are equal” is true -> no difference

The Kruskal–Wallis test by ranks “one-way ANOVA on ranks [1]”

- non-parametric method
- testing whether samples originate from the same distribution
- extends the Mann–Whitney U test

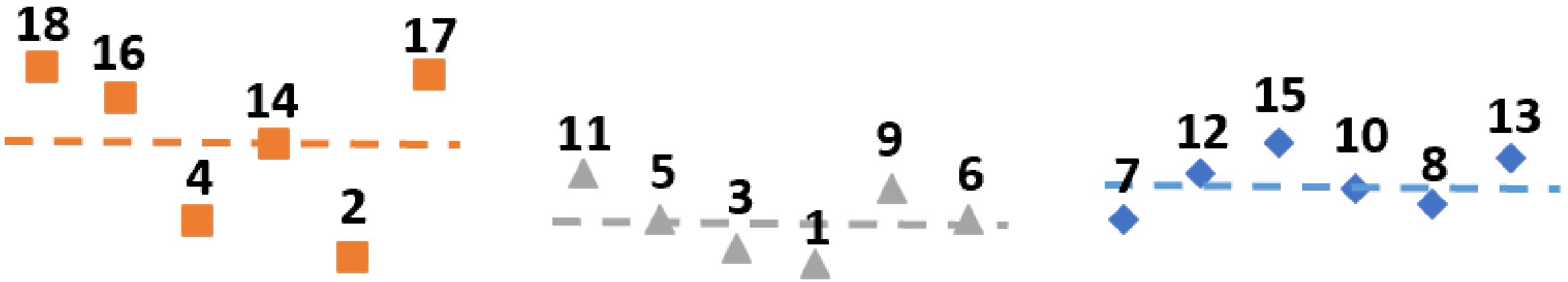
Assumptions:

- It is used for comparing two or more independent samples
- equal or different sample sizes.

$$H = (N-1)\frac{\sum_{i=1}^{g} n_i(\bar{r}_{i\cdot} - \bar{r})^2}{\sum_{i=1}^{g}\sum_{j=1}^{n_i}(r_{ij} - \bar{r})^2}, \text{ where}$$

- N is the total number of observations across all groups
- g is the number of groups
- n_i is the number of observations in group i
- r_{ij} is the rank (among all observations) of observation j from group i
- $\bar{r}_{i\cdot} = \frac{\sum_{j=1}^{n_i} r_{ij}}{n_i}$ is the average rank of all observations in group i
- $\bar{r} = \frac{1}{2}(N+1)$ is the average of all the r_{ij}.

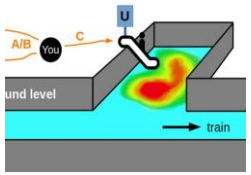
H_0: The mean ranks are equal across 3+ populations.



There is no ideal message design

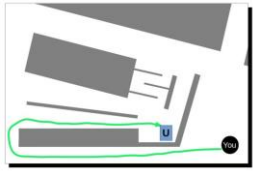
Results of the Mann-Whitney U tests: ■ p-Value < 0.05

Fans



Congestion info

Short	■
Medium	■
Long	■



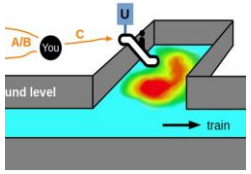
Top-down view

Short	■
Medium	■
Long	

"Team spirit"

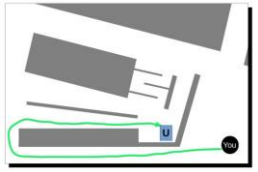
Short	
Medium	
Long	■

Control group



Congestion info

Short	■
Medium	■
Long	



Top-down view

Short	
Medium	
Long	

"Team spirit"

Short	
Medium	
Long	

Gruppe	Reaktionszeit	Rang
Gruppe **A**	34	2
Gruppe **A**	36	4
Gruppe **A**	41	7
Gruppe **A**	43	9
Gruppe **B**	44	10
Gruppe **B**	37	5
Gruppe **B**	45	11
Gruppe **B**	33	1
Gruppe **C**	35	3
Gruppe **C**	39	6
Gruppe **C**	42	8
Gruppe **C**	46	12

Rangsummen:

$R_A = 2 + 4 + 7 + 9 = 22$

$R_B = 10 + 5 + 11 + 1 = 27$

$R_C = 3 + 6 + 8 + 12 = 29$

Mittlere Rangsumme:

$\overline{R}_A = 22 / 4 = 5,5$

$\overline{R}_B = 27 / 4 = 6,75$

$\overline{R}_C = 29 / 4 = 7,25$

$$E_R = \frac{n + 1}{2} = \frac{12 + 1}{2} = 6,5$$

Wir haben bei zwölf Personen die Reaktionszeit gemessen, daher ist die Anzahl der Fälle zwölf. Die Freiheitsgrade ergeben sich durch die Anzahl der Gruppen minus eins, also haben wir zwei Freiheitsgrade.

Anzahl der Fälle

$n = 12$

Freiheitsgrade

$df = 2$

Varianz von Rängen

$$\sigma_R^2 = \frac{n^2 - 1}{12} = \frac{12^2 - 1}{12} = 11,92$$

Erwartungswert der Rangplätze

$E_R = 6,5$

Mittlere Rangsummen:

$\overline{R}_A = 22 / 4 = 5,5$

$\overline{R}_B = 27 / 4 = 6,75$

$\overline{R}_C = 29 / 4 = 7,25$

Prüfgröße H → entspricht χ^2

$$H = \frac{n - 1}{12} \cdot \sum_{i=1}^{k} \frac{n_i (\overline{R}_i - E_R)^2}{\sigma_R^2}$$

$$H = \frac{12 - 1}{12} \cdot 4 \frac{(5,5 - 6,5)^2 + (6,75 - 6,5)^2 + (7,25 - 6,5)^2}{11,92}$$

$= 0,5$

Nachdem der H-Wert bzw. der Chi-Quadrat Wert berechnet worden, kann der kritische Chi-Quadrat Wert aus der Tabelle der kritischen Chi-Quadrat-Werte abgelesen werden.

Chi-Quadrat Tabelle

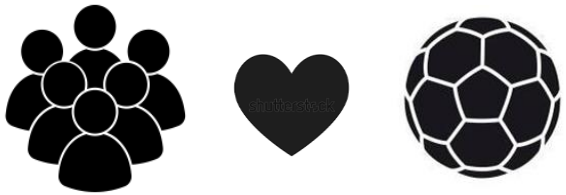
Signifikanzniveau Alpha	0,995	0,975	0,2	0,1	0,05	0,025	0,02	0,01	0,005
Freiheitsgrade									
1	0	0,001	1,642	2,706	3,841	5,024	5,412	6,635	7,879
2	0,01	0,051	3,219	4,605	5,991	7,378	7,824	9,21	10,597
3	0,072	0,216	4,642	6,251	7,815	9,348	9,837	11,345	12,838
4	0,207	0,484	5,989	7,779	9,488	11,143	11,668	13,277	14,86
5	0,412	0,831	7,289	9,236	11,07	12,833	13,388	15,086	16,75

Bei einen Signifikanzniveau von 5% ist der kritische Chi-Quadrat Wert daher 5,991. Dieser kritische Wert ist also größer als der berechnete Chi-Quadrat- bzw. H-Wert. Somit wird die Nullhypothese beibehalten und es gibt keinen Unterschied in der Reaktionszeit in den drei Gruppen.

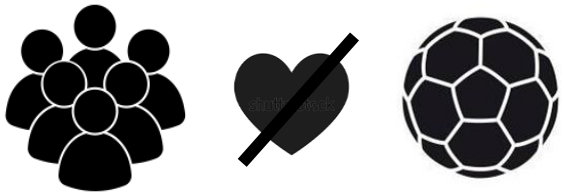
Online survey [28]: football fans and control group, 8 designs

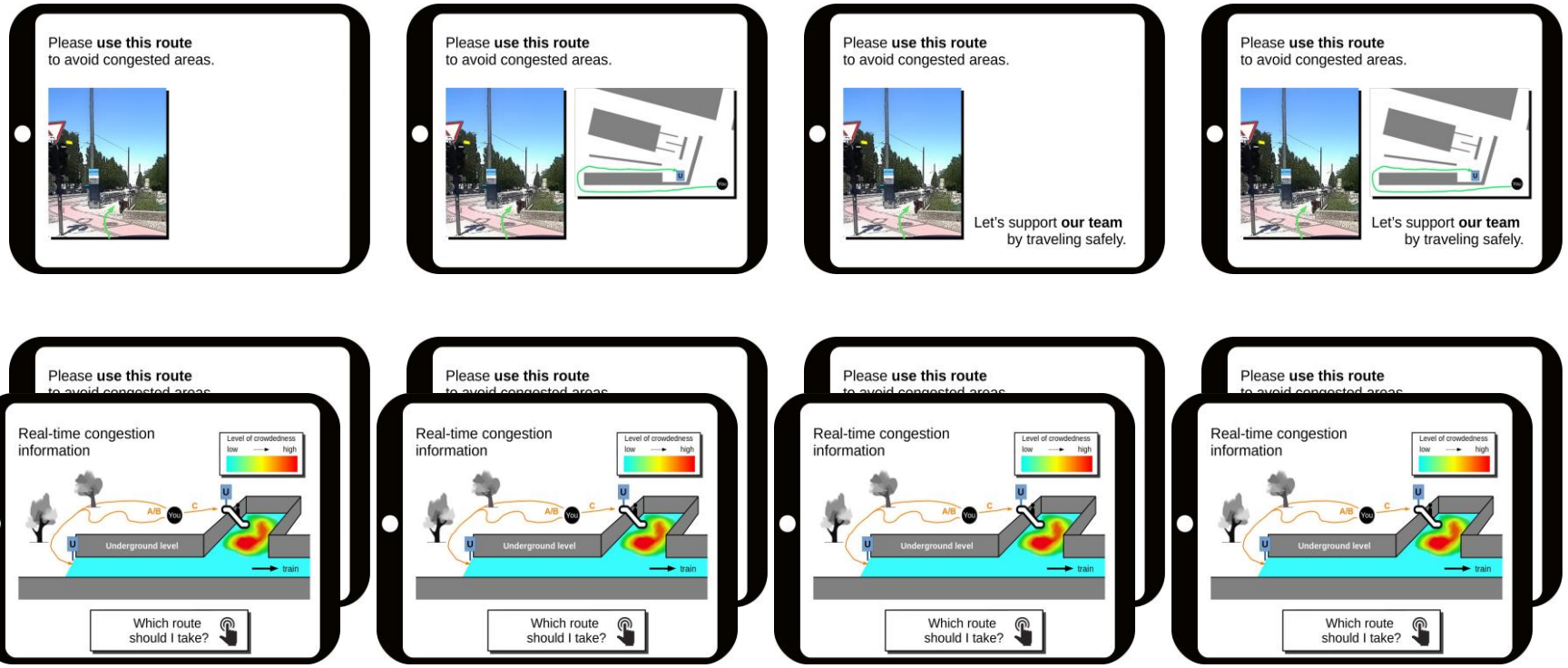
Assumption: fans share a social identity (the control group does not)

Fans 921 participants

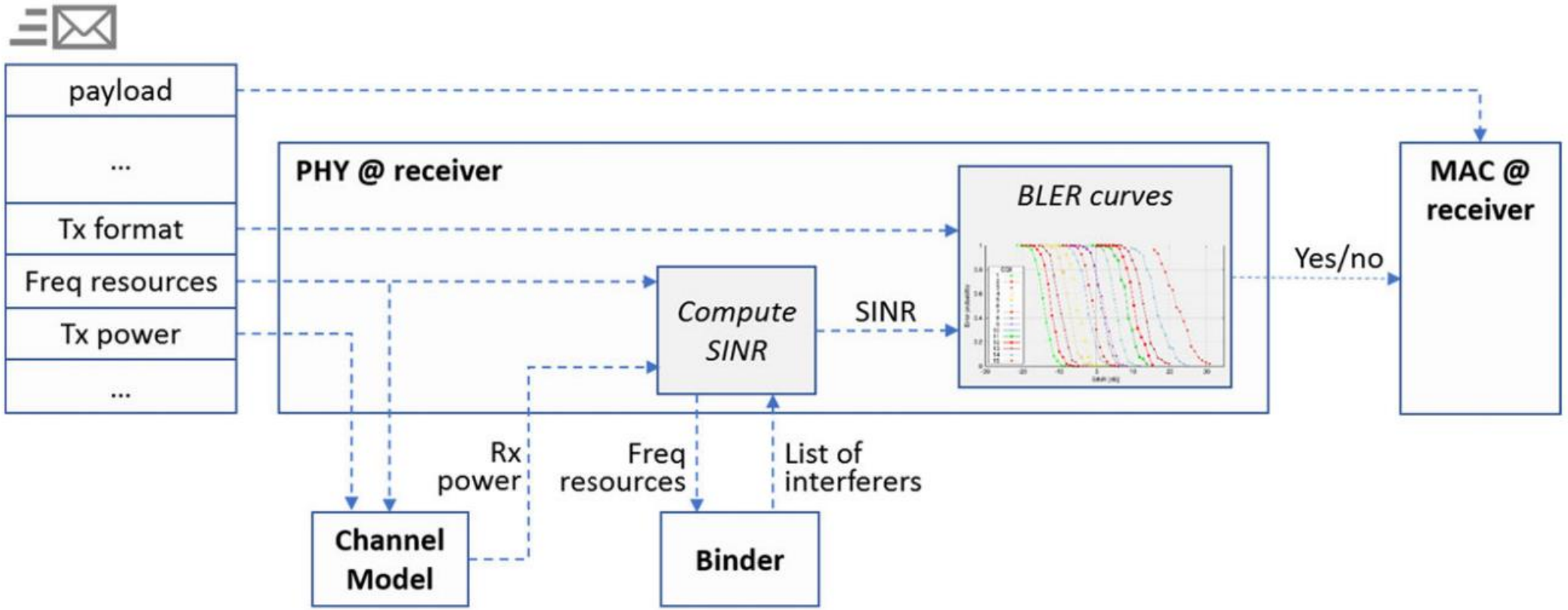


Control 444 participants





simu5G: model structure



Resource Blocks (RBs)

- Starting from the transmitted power at the sender, it applies a *channel model* to compute the received power. A channel model can be configured to incorporate fading, shadowing, pathloss, etc., and can be made arbitrarily complex. Simu5G comes with a default channel model called *Realistic Channel Model*, which is compliant with the 3D model described in [19].
- On each RB occupied by the TB, it computes the SINR as $SINR = P_{RX} \Big/ \left(\sum_j P^j_{RX} + R\right)$, where P_{RX} is the received signal power, P^j_{RX} is the power received from the j-th interferer and R is the Gaussian noise. The set of indexes j is computed by querying the Binder to know which other nodes were using the same RB. For each interferer, the received power is computed by applying the channel model, starting from the transmission power.
- Then, it uses Block Error Rate (BLER) curves to compute the reception probability for each RB composing the ongoing transmission. BLER curves can be obtained from a link simulator or from 3GPP documents. This makes it possible to translate a SINR and a transmission format to a probability of correct reception of an RB. More specifically, the `error()` function considers the BLER curve related to the MCS used in transmission, at the abscissa represented by the measured SINR, and it obtains an error probability for that RB, call it P_{err}.
- Finally, a uniform random variable $X \in [0; 1]$ is sampled and the *AirFrame* is assumed to be corrupted if $X < 1 - \prod_i \left(1 - P^i_{err}\right)$, and correct otherwise.