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Digital evidence, 'absence' of data and ambiguous patterns of reasoning☆

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A B S T R A C T

In this paper we discuss the use of digital data by the Swiss Federal Criminal Court in a recent case of attempted homicide. We use this case to examine drawbacks for the defense when the presentation of scientific evidence is partial, especially when the only perspective mentioned is that of the prosecution. We tackle this discussion at two distinct levels. First, we pursue an essentially non-technical presentation of the topic by drawing parallels between the court's summing up of the case and flawed patterns of reasoning commonly seen in other forensic disciplines, such as DNA and particle traces (e.g., gunshot residues). Then, we propose a formal analysis of the case, using elements of probability and graphical probability models, to justify our main claim that the partial presentation of digital evidence poses a risk to the administration of justice in that it keeps vital information from the defense. We will argue that such practice constitutes a violation of general principles of forensic interpretation as established by forensic science literature and current recommendations by forensic science interest groups (e.g., the European Network of Forensic Science Institutes). Finally, we posit that argument construction and analysis using formal methods can help replace digital evidence appropriately into context and thus support a sound evaluation of the evidence.

Introduction

Preliminaries and case description

The case discussed here pertains to an appeal formed by A. to the Swiss Federal Criminal Court against an extension of his pretrial detention.[2] A. is being investigated by the Office of the Attorney General (OAG) of Switzerland on suspicion of attempted intentional homicide (art. 111 in conjunction with art. 22 of the Swiss Criminal Code) and endangering by explosives and toxic gases with criminal intent (art. 224 of the Criminal Code).

The facts, as presented by the prosecution, are as follows. A.'s estranged wife, B., was walking down a sidewalk in the city of Z. (Switzerland) at 6:30AM one morning when she was hit by a hand grenade thrown at her. The explosion caused her injuries to the abdomen and to her left hand. B. testified that she had not seen who had attacked her, but said that A. had been following her for some time. At the crime scene, the police were able to locate the detonation point and saw several indentations on the curb of the pavement. The police also seized several fragments of plastic, small metal balls and a lever, all identified as constituting elements of a model of hand grenade used by the former Yugoslavian army. During his first interrogation by police, A. said that he was in Bosnia and Herzegovina at

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[2] Swiss Federal Criminal Court, decisions BH.2014.16 and BP.2014.59.

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the time of the crime. However, subsequent police investigation revealed that A. had crossed the Swiss border into Italy approximately 5 h after the attack on B. took place.

There are two items of scientific evidence in this case. The first is a DNA-profile established from a swab of the surface of the lever of the hand grenade. This DNA was found to correspond to the DNA-profile of A.[3] The second item of interest is so-called digital evidence, i.e. a technical report about analyses of telecommunication and navigation data carried out on A.'s mobile devices. According to a report issued by the Federal Criminal Police (FCP), *no* signals of A.'s mobile devices were detected on the crime scene at the time B. was attacked.

Aims and structure of the paper

In the remainder of this paper, we will take a closer look at the way in which the digital evidence mentioned above was used by the Swiss Federal Criminal Court to justify prolonging A.'s pretrial detention, based on the judgement of the court as it was published.[4, 5] It is not our intention to question the court's decision in this case. The case is selected for the sole purpose of illustrating the actuality and relevance of the topic. At times, our discussion will include references to a recently published European guideline for evaluative reporting in forensic science (ENFSI, 2015) as well as established principles of forensic interpretation.

Case analysis: digital evidence

The court's summing up

In its written judgement, the Swiss Federal Criminal Court summed up the digital evidence in this case in a single sentence (Section 3.3):

> “At the time of the crime, no mobile device belonging to A. could be located at the scene.”[6]

The court then used this piece of information received from the FCP to support the following claim:

> “This investigative result does not necessarily exclude that the complainant [Mr. A.] could have been present at the crime scene at the time when the crime was committed.”[7, 8]

These two sentences are concise, but they contain elements that are useful for the present discussion. In general terms, the court is of the opinion that the digital evidence does not – literally – falsify the prosecution's case. This conclusion raises a series of questions, such as: ‘If the digital evidence does not falsify the prosecution's case, what effect – if any – does it have on the prosecution's case?’ and, equally important, ‘What – if anything – does the digital evidence say with respect to A.'s case?’. In the next sections, these questions will first be approached from a general perspective, invoking legal (Section Legal considerations) and scientific criteria of evaluation (Section General observations). Attention will be drawn to potentially ambiguous reasoning patterns and parallels to argumentative drawbacks commonly encountered with other types of scientific evidence. The outcomes of this discussion will be contrasted, in Section Principles of scientific interpretation, with a formal analysis of the case using standard elements of probability and graph theory.

Legal considerations

The written judgement issued by the Swiss Federal Criminal Court in this case[9] examines the question of whether A.'s pretrial detention should be prolonged. At this stage, the court does not evaluate the evidence fully, but only considers whether the four following conditions are fulfilled (art. 221 Swiss Code of Criminal Procedure): a) there is a strong suspicion b) that the suspect committed a felony; c) there is a serious risk of flight, of reoffending or of tampering with the evidence; and d) the duration of pretrial detention is proportionate with regards to the sentence that will likely be imposed by the court in case of conviction.

In this case, the question is thus whether the evidence presented by the prosecution is strong enough to entail a strong suspicion that A. threw a hand grenade at his wife and that there is a risk of flight, reoffending or tampering with the evidence. The burden of proof lies with the prosecution, but there is no strict standard of proof in the field of pretrial detention: the evidence will have to be all the more stronger that the proceedings are advanced and that the case is close to being sent to trial, but it does not need to reach any given threshold. Conversely, at the onset of an investigation, it is acceptable to base the decision to put the suspect in pretrial detention on evidence that is still somewhat weak. To remedy this weakness, more evidence is adduced. In this context, credible evidence of innocence is not necessarily enough to prohibit authorities from imposing pretrial detention, if it is countered by credible evidence of guilt.[10]

In the present case, the court held that the digital evidence did not falsify the hypothesis presented by the prosecution. Although legitimate at this stage of the proceedings, this is a limited and partial perspective, in that it

[3] This paper does not deal with the issue of the probative strength to be assigned to this correspondence.

[4] Above n 2.

[5] Note that this is our only source of information regarding the case.

[6] Translation and text between brackets added by the authors. The original sentence is: “zum Tatzeitpunkt [konnten] keine Verkehrsdaten der Mobilfunkgeräte des Beschwerdeführers geortet werden”.

[7] Translation and text between brackets added by the authors. The original sentence is: “Schliesst doch dieses Ermittlungsergebnis nicht zwangsläufig aus, dass sich der Beschwerdeführer zum Tatzeitpunkt am Tatort befunden haben könnte”.

[8] Note that the transcript is silent about further details regarding the perimeter of what is referred to as the ‘crime scene’. Further discussion about technicalities of geographic location using mobile devices is beyond the scope of this paper.

[9] Above n 2.

[10] In the adjudication stage, however, the accused cannot be convicted if the court has not reached the firm conviction that the accused is guilty – a standard similar to proof beyond a reasonable doubt.

says nothing of the strength of the evidence in light of the hypothesis presented by the defense (i.e., that the accused was not at the crime scene at the time of the attack). Excluding this aspect from the discussion, the court conveys the view that the prosecution's case stands unaffected by the evidence, meaning that the evidence is actually neutral. Forensic science literature and practice teach that this perspective is not optimal, as the following sections will aim at demonstrating.

General observations

'Consistent with'

In essence, the court in this case finds the scientific evidence to be 'consistent with' the complainant being on the crime scene. This is conveyed, in particular, by the formulation 'could have been present at the crime scene'. It is worth noting that both the notion of 'consistent with' and qualifiers of possibility such as 'could have', 'might' and 'cannot be excluded' hold a precarious status in evaluative criminal casework (Evett, 2015; Aitken et al., 2010).

First and foremost, sentences containing such expressions are *not* propositions in the proper sense, but amalgams of propositions and personal beliefs about propositions. Propositions are sentences of the kind 'A. was on the crime scene', which may either be true or false. Additions such as 'could' or 'might', on the other hand, express one's belief in the truth or otherwise of the proposition. This is little informative, as it expresses only that one maintains a probability different from zero. To be informative, one ought to specify in a more explicit way how much credibility one attaches to the proposition at hand.

Besides the confusion between possibilities and propositions, terminology of the kind 'consistent with' is also defective because of its imbalance. That is, stating only that evidence is consistent with the complainant being on the crime scene, and leaving it with that, is a prosecution-sided account (also sometimes referred to as biased). Such an account is imbalanced because it does not specify the extent to which evidence is *also* consistent with other propositions. Mentioning the prosecution's proposition as the only view thus gives, indirectly, the logically false impression that this view is also the most plausible.

Aitken et al. (2010, p.60) provide a telling example for the points mentioned above: "(…) buying a ticket is consistent with winning the National Lottery, but it does not make winning very likely. Buying a ticket is also consistent with *not* winning the National Lottery, and this second outcome is very much more likely than the first, though both are equally "consistent with" the premiss (buying a ticket)."

Convenience conclusions

Further, expressing one's belief with respect to only a single proposition is akin to framing conclusions around a preferred proposition, that is at one's convenience, *whatever* the evidence actually available. In the context of digital evidence, this can be illustrated as follows. When the case is such that signals of a mobile device were detected, one would conclude that such a finding is consistent with the proposition according to which the owner[11] of the mobile device was on the crime scene. In turn, in a case with no detected signal – as is the case considered in this paper (Section Preliminaries and case description) – one would still conclude that such a 'negative finding' does not rule out the proposition according to which the owner of the mobile device was on the crime scene. Thus, whatever the finding (i.e., the presence or absence of signals) the prosecution's case is found to be compatible. Yet, by the same line of argument, one could also retain conclusions with respect to the proposition of *not* being on the crime scene, whatever the evidence being found.

Moreover, even though the finding of a signal stands well in agreement with the presence at the crime scene, such a conclusion is disturbing for a case in which no signal was recorded. The reason for this is that it takes little effort to imagine the mass of individuals[12] for whom the same conclusion could be reached, based on the absence of a recorded signal of their mobile device – due to various entirely plausible reasons (e.g., because they have no connection whatsoever with the crime scene).

Parallels to conclusion patterns seen with other forensic evidence types

The argumentative impasse outlined in the previous section is similarly encountered with other, more traditional items of scientific evidence. Take, for example, material found on a crime scene, potentially left by the offender, such as trace quantities of DNA. For such evidence it is common to conclude that if a crime stain has the same analytical features as a potential source (i.e., a suspect), then the crime stain is 'consistent with' the proposition according to which the crime stain comes from this potential source (Taroni et al., 2002). Alternatively, the potential source is also said to be 'not excluded'. This view is often supported by deductive-nomological explanation schemes based on statements such as "[i]f a stain of organic liquids comes from a person, and it has not been in contact with extraneous organic material, then the stain shares the DNA profile of that person" (Taroni et al., 2006, p.26).[13]

Now does this mean that if the crime stain is *lacking* features seen in reference material coming from a potential source, one ought to conclude that such a finding is *not* consistent with the proposition according to which the trace material comes from the potential source? The answer – contrary to what one might expect – is no. In the current state of DNA analyses, in particular if the trace material is present in very low quantities, it is not uncommon for some features to get 'lost' or go undetected.

[11] At this juncture, the term 'owner' is used in a generic sense without distinction with respect to users or keepers who are not owners. More formal developments of argument structures later on in the paper will endeavour to overcome this simplification.

[12] We also leave aside, at this juncture, considerations about the relevant population, which may informed by circumstantial information.

[13] We emphasize that the real problem here is not deductive, that is reasoning from propositions to potential findings, but inductive, that is reasoning about propositions on the basis of particular findings. Later parts of this paper will deal with the logical framework to approach the latter task.

This phenomenon is commonly called ‘drop-out’ (e.g., Balding and Steele, 2015). Similarly, when the crime stain has features not seen in the reference material of a potential source, scientists may invoke an event called ‘drop-in’. In summary, thus, we see the same scheme of reasoning as encountered in the previous section: whatever the finding, it is possible to shape an argument in such a way that the prosecution's story (i.e., the trace comes from the potential source) is not excluded.

A further common example are gunshot residue (GSR) particles. When a cartridge is fired by a firearm, discharge residues are produced. They consist of a variety of materials and their analysis is of interest from a forensic point of view because they deposit in the vicinity of the discharging firearm, in particular hands, face and clothing of shooters and bystanders. In this context, the expression ‘consistent with’ is used to refer, for example, to the detection of GSR particles on hands when the prosecution's proposition is that the person is the shooter.[14] However, consider now the *absence* of detected particles. In such a context, scientists may state:

> “The absence of gunshot residue on a person's hands does not eliminate that individual from having discharged a firearm.” (Trimpe, 2011, at p.29)

They may also argue that:

> “[i]f a subject has washed or cleaned the hands in some manner, the likelihood of detecting GSR decreases. The hands may have been covered with gloves or some other covering. For these reasons and many others, negative results obtained from an examination are not necessarily exculpatory.”[15] (Schwoeble and Exline, 2000, at p.127)

In summary, thus, whatever the scientist's result (i.e., presence or absence of GSR particles), it is found ‘consistent with’ the prosecution's case of discharging a firearm.

Clarifying the nature of the report

Given the observations outlined in the previous sections, one might respond that the various quotes and examples have been presented beyond a particular context of application, which creates the false impression that results of forensic examinations can be deliberately adducted to support any proposition of interest. We do not intend to make this claim. Rather, we wish to make the point that preferential and incomplete discussion of forensic findings, be it digital evidence, DNA or GSR, is liable to imbalanced conclusions. Scientific and technical evidence is used, however, in different ways and for distinct purposes at the various stages in the legal process, which is why it is important for discussants to clarify at which stage and in which process they operate (Anderson and Twining, 1998).

It is equally important to take into account the nature of the reports issued by scientists because the scope and purpose may vary according to different report categories. A recently issued guideline by the European Network of Forensic Science Institutes (ENFSI) (ENFSI, 2015) distinguishes between three main categories. A first category regards technical reporting. It amounts, in essence, to the reporting of observations in a descriptive way without elaborating on any propositions, except where propositions relate to general categories of classification (e.g., a scientist classifies fragments as glass or paint). Such a descriptive account is a preliminary for a second category of reports: investigative reports. Such reports explore explanations for particular observations and are useful at an early stage of investigation when the aim is to reconstruct events of interest, or to give leads regarding the potential source of material recovered on the crime scene (e.g., provision of information about the model and make of a car). Descriptive accounts are also a preliminary for a third category of reports: evaluative reports. This type of report is used in more advanced stages of the process, when a potential source is available and comparative examinations with trace material have been conducted (e.g., the DNA profile of a crime stain is compared to the DNA profile of a suspect). This last type of report is called ‘evaluative’ because a potential source is available (which is not typically the case for the technical and investigative reporting) and the result of the comparative examinations has the potential to crucially impact on the defendant's position at trial.

In the case discussed here, the digital evidence takes the form of what is referred to as a “technical evaluation of telecommunication and navigation data”, and is seen as an “investigative result”.[16] Supposedly, this technical report is limited to technical reporting as defined above, that is a statement regarding the presence or absence of detected signals of mobile phone devices. While the investigative value of such information is clear (i.e., detected mobile device signals allow one to select candidate suspects for further examination), it is worth noting that the subsequent use of such information at trial represents a distinct situation. A trial is not about exploring potential explanations for the findings in an informal and deliberate way, but an instance where two sides oppose competing scenarios, and the purpose is to weigh the evidence against those two positions. A conclusion that refers to only one proposition (e.g., that of the prosecution) and that is limited to an expression of the kind ‘cannot be excluded’ is thus both incomplete and unbalanced.

In Section Principles of scientific interpretation, we will discuss an established framework for thinking about the strength of forensic evidence, based on elements of probability theory. We will critically review the court's conclusion and examine the insight that the framework can provide for the digital evidence of the case considered in this paper.

[14] Note that this is just one example for a proposition. Generally, forensic GSR examiners insist on specifying a series of further propositions, such as being a bystander, manipulating a contaminated object, etc. See (Gallidabino et al., 2013) for a discussion of problems with unordered listings of potential explanations and (Evett, 2015) for an example of the use of ‘consistent with’ in a real case involving GSR.

[15] Note the parallel between the last sentence in this quote and the court's summing up for the digital evidence considered in this paper (Section The court's summing up).

[16] Above n 2 (Section 3.3).

Principles of scientific interpretation

The question triad and the three principles

A common pattern of argument seen throughout Section Case analysis: digital evidence involves two steps: first, a statement about what has been observed, and second, a concluding statement about a *single* proposition, usually that of the prosecution. It has also been observed that it remains obscure how the transition between the observations and the statement is made. Most importantly, it remains obscured what the finding might mean with respect to an alternative proposition.

To overcome these drawbacks, it is now widely argued in both scientific and legal literature that the scientist's findings, when considered at an evaluative stage (Section Clarifying the nature of the report), should be structured along three questions (e.g., Aitken et al., 2010; Robertson and Vignaux, 1993; Bender et al., 2007): first, 'what is the probability of the evidence given the prosecution's case and the case circumstances', second, 'what is the probability of the evidence given the defense's case and the case circumstances', and third, 'under which proposition are the findings more probable, under the first or the second proposition'? This question triad will single out the proposition, if any, which is supported by the evidence, compared to the alternative. In particular, if the evidence is more probable given the first proposition rather than given the second proposition,[17] then the evidence supports the first proposition, and vice versa. If the evidence is equally probable under both propositions, the evidence does not help discriminate between the two propositions, and is neutral.[18]

The question triad emphasizes three principles of forensic interpretation (e.g., Evett and Weir, 1998). First, it clarifies that evaluation is conditioned by a framework of circumstances. Second, forensic results ought to be looked at from at least two competing viewpoints. Third, by focussing on the probability of the evidence *given* propositions, rather than the opposite, the scientist will avoid interfering with the role of the judicial decision maker.

Pre-assessment

Before applying the principles exposed in Section The question triad and the three principles to the current case, it is relevant to mention yet another evaluative device: pre-assessment. Pre-assessment is intended to avoid post-hoc rationalisations. Pre-assessment is a methodology that seeks to avoid this by (i) specifying potential results *prior* to performing any analyses, (ii) assessing the probative value for each potential finding, and (iii) assigning probabilities with which the various results may be obtained under each of the competing propositions (Cook et al., 1998; Jackson et al., 2013). This procedure adds credibility to the scientist's evaluation because the strength of the findings is thought about before conducting examinations and obtaining actual findings.

Table 1
Probabilities Pr to be addressed in pre-assessment for findings E given propositions H and information I as defined in Section Application to the present case.

Propositions:	H_p	H_d
Findings: E:	$\Pr(E\|H_p, I)$	$\Pr(E\|H_d, I)$
$\bar{E}$:	$\Pr(\bar{E}\|H_p, I)$	$\Pr(\bar{E}\|H_d, I)$

Application to the present case

Start by considering the case of interest here from a general perspective by supposing that the actual findings are not yet available. Such a starting point can help focus on generic case properties and provide guidance in similar cases. There are two propositions of interest to the court. Let them be denoted H_p, 'A. is the person who threw the hand grenade at the victim',[19] and H_d, 'A. was nowhere near the scene of the crime when the grenade was thrown (an unknown person threw the grenade)'.[20] The information I relates to the time and location of the crime. Let the potential findings be denoted E, 'signals of A.'s mobile devices were detected in the crime scene area during the time interval when the explosion occurred', and $\bar{E}$, 'no such signals were detected'.

To elicit the probative value of the possible outcomes E and $\bar{E}$, it is necessary to assign values for the probabilities defined in Table 1. For the result E, 'signals of A.'s mobile devices were detected in the crime scene area during the time interval when the explosion occurred', any person interested in the capacity of this finding to discriminate between H_p and H_d needs to consider the following three questions (Section The question triad and the three principles): 1. how probable is the finding E if A. was on the crime scene ($\Pr(E|H_p, I)$)? 2. how probable is the finding E if A. was nowhere near the crime scene ($\Pr(E|H_d, I)$)? 3. is the finding E more probable given H_p or given H_d?

The above questions raise several important remarks. First and foremost, the questions highlight the importance of the conditioning information I for the assignment of probabilities. For instance, the assessment of $\Pr(E|H_p, I)$, that is the probability of detecting signals if A. is the offender,

[17] In technical language, this is amounts to a likelihood ratio greater than 1 (e.g., Aitken and Taroni, 2004).

[18] In the remainder of this paper, standard notation E, H, I and Pr will be adopted for, respectively, evidence, propositions (also called hypotheses), conditioning information and probability.

[19] This proposition is equivalent to the proposition 'A. is the offender'. Note that B. testified during investigation that a third person was asked by A.'s brother to kill B., and that this third person told B. about this conversation. However, at this stage of the process, the court does not formally maintain a scenario in which A. hired a third party to commit murder. Should this assumption change, then it will be necessary to review the current analysis.

[20] These propositions are at an advanced level in the hierarchy of propositions (Cook et al., 1998) and approach the competing positions presented at trial most closely. Despite occasional objections by scientists, it is not problematic to assess scientific findings given such propositions because scientists will focus on the results only, and not on the propositions themselves (see also Section The question triad and the three principles).

makes it relevant to take into account whether A. possesses any mobile devices, how he uses them and whether he would switch off his devices if he were on the scene at the time of the attack (i.e., if he were the offender). Similarly, if A. had nothing to do with the case, the probability of detecting signals can be informed by aspects such as the place where A. lives (e.g., in the vicinity of the crime scene?), who else had access to his mobile devices (and use them) and A's reported activities at the time of the assault on B.

As a second comment, it might be objected that defining values for $\Pr(E|H_p,I)$ and $\Pr(E|H_d,I)$ is overwhelmingly difficult. Yet, these are the fundamental terms to be addressed by anyone who wishes to sort out, on a logical account, which if any of the two propositions H the evidence E supports over the respective alternative. It follows from this that anybody unwilling or feeling unable to express an opinion on the above two key terms should be withheld from using evidence E, on pain of lacking the grounds for a logically supported conclusion. It is worth mentioning, though, that the assignment of particular numerical values is not immediately necessary in a first approach. Indeed, qualitative probability (e.g., Wellman, 1990; Biedermann and Taroni, 2006) allows one to make the following distinctions, in agreement with the principles outlined in Section The question triad and the three principles:

- $\Pr(E|H_p,I) > \Pr(E|H_d,I)$: If, on a qualitative account, an evaluator considers E to be more probable given H_p than given H_d, then for this evaluator the ratio of these two probabilities, called the likelihood ratio,[21] is greater than 1 and hence evidence E supports H_p over H_d.
- $\Pr(E|H_p,I) < \Pr(E|H_d,I)$: If, on the other hand, an evaluator considers E to be more probable given H_d than given H_p, then for this evaluator the likelihood ratio is smaller than 1 and hence evidence E supports H_d over H_p.
- $\Pr(E|H_p,I) = \Pr(E|H_d,I)$: If an evaluator considers E to be equally probable under the two competing propositions H_p and H_d, then for this evaluator the likelihood ratio is 1 and hence evidence E does not help discriminate between the competing propositions.

Qualitative probabilistic reasoning thus allows one to assess which, if any, of the two propositions the evidence supports over the alternative. Making assessments numerically precise is only necessary if one also wishes to clarify by *how much* one proposition is supported over the respective alternative. For example, if one considers that $\Pr(E|H_p,I)$ is about a hundred times greater than $\Pr(E|H_d,I)$, then the effect of the evidence E can be summarised as follows: 'Whatever your assessment is that A. is the offender on the basis of other evidence, consideration of the evidence E multiplies your odds by about 100'.[22]

As a third point of discussion, it is worth noting that the way in which evaluators assess $\Pr(E|H_p,I)$ and $\Pr(E|H_d,I)$ determines the probative value of the alternative outcome $\bar{E}$, i.e. no detected signals. This is so because the values in the columns of Table 1 sum to 1 and hence a qualitative statement about $\Pr(E|H_p,I)$ and $\Pr(E|H_d,I)$ will, as a matter of coherence, determine $\Pr(\bar{E}|H_p,I)$ and $\Pr(\bar{E}|H_d,I)$. For example, imagine that an evaluator holds the view that in the case at hand, given the case circumstances, detecting signals of A.'s mobile devices is more probable given H_p than given H_d (i.e., $\Pr(E|H_p,I) > \Pr(E|H_d,I)$). This may be so even though the evaluator considers that $Pr(E|H_p,I) < 1$, because A may have taken measures to prevent his mobile devices' signals from being detected. It follows from this that the likelihood ratio for finding E is greater than 1 and supports H_p over H_d. It is interesting now to note that the assessment $\Pr(E|H_p,I) > \Pr(E|H_d,I)$ implies that $\Pr(\bar{E}|H_p,I) < \Pr(\bar{E}|H_d,I)$: it is more probable not to detect any signals if A. was nowhere near the crime scene than if he was on the crime scene. This expression of qualitative beliefs amounts to a likelihood ratio smaller than 1, which implies support for the defense proposition (H_d) rather than the prosecution's case (H_p). This allows us to come back to the court's conclusion presented in Section The court's summing up. While a likelihood ratio smaller than 1, but greater than zero, reduces the odds in favour of H_p, such a result would not 'falsify' H_p. The court's conclusion regarding the possibility that A. was present at the scene is not in conflict with this view. However, the court's statement is incomplete in the sense that it remains silent about the effect of observing no signal ($\bar{E}$). In particular, if the court accepts that detecting no signals is more compatible with H_d than with H_p, it agrees with the qualitative expression $\Pr(\bar{E}|H_p,I) < \Pr(\bar{E}|H_d,I)$, which represents an expression of strength of evidence in favour of H_d. The conclusion of our analysis thus is that, under the stated assumptions, the court's silence regarding the impact of the findings on the alternative proposition implies that information favourable to the defendant is not duly acknowledged.

As a fourth comment, it is relevant to mention that, despite the above argument invoking the notion of probability to describe what an evaluator expects to see given each of the two competing scenarios (H_p and H_d), this does *not* refer to frequency or relative frequency.[23] In particular, there is no requirement for the findings to be conceivable in terms of a sequence of trials under comparable conditions, nor is such an idea meaningful in the first place. The case at hand is unique in its own right, including the case circumstances. Hence, evaluators are required to think about *this* case, which entails formulating expectations about a singular event, and not an instance of an imaginary sequence of trials. Accordingly, it is the belief-type interpretation of probability that is operationally feasible[24] here and potential objections regarding the difficulty of 'reconstructing' the probabilities of interest in a frequentist perspective can be

[21] See above n 17.

[22] Structure of the sentence adopted from Robertson and Vignaux (1995), at p.65. Note that this is only an example and there are other acceptable ways to translate a likelihood ratio verbally.

[23] See Lindley (2014) on the distinct meanings of probability and frequency, and Biedermann (2015) for a discussion of this topic in the context of forensic science.

[24] See Lad (1996) regarding the notion of operational definitions of probability.

dismissed. The task of evaluating the digital evidence thus is not one of classical statistics, but a more general one, involving principles of reasonable reasoning in the face of uncertainty. As argued throughout this section, the availability of precise numerical assignments is not a necessary requirement. Qualitative expressions of belief or at least expressions of relative orders of magnitude may be sufficient.

As a last comment, it is worthy to mention that this analysis does also allow for the consideration that A.'s device was present but not turned on. As noted by a reviewer of this paper, if a crime involves premeditation, it is relevant to consider that the perpetrator takes precautions not to leave detectable traces. In probabilistic language, accounting for this consideration would mean that $\Pr(E|H_p,I)$, the probability of detecting signals given that A. is the offender, is assigned a low, or even a very low value. This will obviously impact on the value of the likelihood ratio. Note that in the extreme case where one would consider the probability $\Pr(E|H_p,I)$ as low as $\Pr(E|H_d,I)$, that is the finding of a signal if an unknown person were the offender, then the finding E would lead to a likelihood ratio of 1, that is a neutral result (i.e., which would not impact on the evaluator's view of the case).

Extended analysis

The framework of probabilistic reasoning invoked in Section The question triad and the three principles is formulated at the most general level of abstraction, involving only two variables, target propositions H and findings E. Despite its generality, the framework is helpful to point out that a balanced assessment requires the evidence to be thought of not only given the prosecution's case (H_p), but also given at least one alternative proposition (here H_d). The framework also emphasizes that the scientist's reasoning should focus on the probability of the findings given the propositions, and not the reverse. But still, practitioners may object that terms such as $Pr(E|H_p,I)$ are too general and difficult to assign, because of an overwhelming amount of intermediate reasoning steps and considerations that may be invoked. This, however, does not prevent probabilistic reasoning from being applied both in this case and in general because there are ways to formulate and implement probabilistic reasoning schemes at more advanced levels of complexity. One such way are graphical probabilistic models, known as Bayesian networks (BNs) (e.g., Taroni et al., 2014; Roberts and Aitken, 2013). In this section, we describe how this modelling framework may be used in a given case to render additional considerations in digital evidence interpretation explicit and to incorporate them into the reasoning process.[25]

Fig. 1 depicts a Bayesian network where the nodes H and E represent the binary propositions ‘A. is the offender’ and ‘Signals of A.'s mobile devices have been detected at the crime scene’, respectively. These propositions are the same as those defined in Section Application to the present case.

[25] See Taroni et al. (2004) for elements of the definition of BNs and methodological elements for the construction of BN model construction.

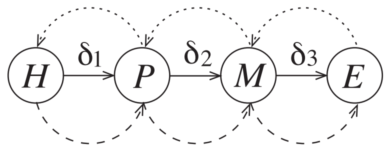

Fig. 1. Bayesian network with four variables defined as follows: ‘A. is the offender’ (H), ‘A. was in the relevant area at the relevant time’ (P), ‘A.'s mobile devices were in the relevant area at the relevant time’ (M), ‘Signals of A.'s mobile devices have been detected in the relevant area at the relevant time’ (E). All nodes are binary. Straight arcs denote relevance relationships. Dashed and dotted arcs denote deductive and inductive reasoning steps, respectively. The δ_i designate the signs of qualitative influence ($\delta_i \in \{+,-,0,?\}$).

Table 2
Conditional probabilities to be assigned for the node tables of the Bayesian network shown in Fig. 1. Variables E, M, P and H are as defined in the text. The last two columns contain exemplary values discussed in Section Extended analysis.

Node states:	Conditional probabilities		Example	
P:	$\Pr(P\|H_p,I)$	$\Pr(P\|H_d,I)$	1	0.001
$\overline{P}$:	$\Pr(\overline{P}\|H_p,I)$	$\Pr(\overline{P}\|H_d,I)$	0	0.999
M:	$\Pr(M\|P,I)$	$\Pr(M\|\overline{P},I)$	0.99	0.001
$\overline{M}$:	$\Pr(\overline{M}\|P,I)$	$\Pr(\overline{M}\|\overline{P},I)$	0.01	0.999
E:	$\Pr(E\|M,I)$	$\Pr(E\|\overline{M},I)$	0.9	0.0001
$\overline{E}$:	$\Pr(\overline{E}\|M,I)$	$\Pr(\overline{E}\|\overline{M},I)$	0.1	0.9999

The model involves two additional intermediate propositions that separate E from H to form a structure known as serial connection.[26, 27] The intermediate propositions are P, defined as ‘A. was in the relevant area at the relevant time’, and M, defined as ‘A.'s mobile devices were in the relevant area at the relevant time’. States $\overline{P}$ and $\overline{M}$ denote the negations of the latter two propositions. Unlike Table 1 involving conditional probabilities for E given the competing propositions H, the model here breaks down the reasoning steps into further detail, which leads to the conditional probabilities shown in Table 2. The specification of numerical values for these terms, or qualitative expressions, allows one to acknowledge a variety of considerations that the competing parties at trial may raise. We can illustrate some of these considerations as follows:[28, 29]

- Node P: Given the kind of crime, that is throwing a hand grenade at someone, the offender must be present on the crime scene to commit it. Hence, $\Pr(P|H_p,I) = 1$. In turn, if A. is not the offender, the probability of him being at the crime scene is assigned depending on the

[26] The reasoning patter captured by this structure is also sometimes referred to as cascaded inference (Schum, 1994).

[27] Note that this is a coarse model and further structural refinements may be introduced as required.

[28] We can focus our discussion on the dark shaded cells in Table 2 because the remaining values are found as the difference to 1: e.g., $\Pr(E|M,I) + \Pr(\overline{E}|M,I) = 1$.

[29] Note that we do not intend to make particular claims about the scenario. All assignments are examples only. They are, by definition, personal and it is explicitly assumed that evaluators will specify their own values to reflect appropriately on their positions.

circumstances (e.g., where A. lives, what he says about his whereabouts, etc.). This probability, $\Pr(P|H_d, I)$, may be assigned in a variety of ways, and a value considerably smaller than 1 could find wide intersubjective acceptance. For the purpose of illustration, assume the value 0.001 because A. says that he was nowhere near the scene.

- Node *M*: Here one needs to assess the probabilities of A.'s mobile devices being present on the crime scene (M) given that A. was (P) or was not present ($\bar{P}$) at the crime scene. This requires one to assess the probability of A. carrying his mobile devices with him[30] and the possibility of his mobile devices being on the scene without him being there. Clearly, the latter event appears less plausible than the former unless A. could provide a credible account as to how his mobile devices got to the scene without him (e.g., because the devices were used by more than one person). For the purpose of illustration, let $\Pr(M|P, I) = 0.99$ and $\Pr(M|\bar{P}, I) = 0.001$. The latter assignment supposes that mobile devices are generally not used by more than one person (i.e., the owner) and that this assumption is acceptable for the case here.[31]
- Node *E*: This node requires the assignment of a value for $\Pr(E|M, I)$, the probability of detecting device signals if the devices were present on the crime scene. If there are few reasons to suppose that a device will not be detected, $\Pr(E|M, I)$ should be assigned a value close to 1. Assume the value 0.9, for example. In turn, $\Pr(E|\bar{M}, I)$ requires one to think about the event of detecting a signal of a device that is *not* present. Suppose that this is an implausible event, unless there is some obvious potential for false recordings (e.g., due to error) that needs to be accounted for. Thus, assume that a value of 0.0001 is found acceptable.

With these probability assignments, the likelihood ratio for the finding $\bar{E}$ with respect to the propositions H_p and H_d is in the order of 10 in support of the alternative proposition.[32] Some or even all of the values assigned above, summarised in Table 2, may be subject to variation according to the person in charge of the evaluative process, but this is not a drawback of the current analysis because sensitivity analyses (e.g., Biedermann and Taroni, 2006) can be applied in order to explore the extent to which alternative assignments affect the overall conclusions regarding evidential value.

While there may be disagreement about numerical assignments, it is reasonable to suppose that the qualitative probabilistic relationships can be intersubjectively agreed upon. In particular, considering the values specified in the two columns on the right of Table 2, it appears reasonable to accept that the outcomes *P*, *M* and *E* are *more* probable given the conditioning events H_p, P and M, respectively, rather than given the events H_d, $\bar{P}$ and $\bar{M}$, respectively. These qualitative probabilistic relationships imply that the signs of probabilistic influence δ_1, δ_2 and δ_3, shown in Fig. 1, are positive ($+$).

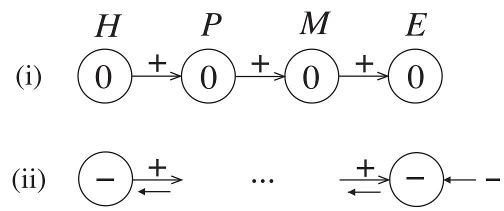

Fig. 2. Qualitative probabilistic network for evaluating digital data based on a model described earlier in Fig. 1: (i) initialised network (the sign of each node is set to 0), (ii) illustration of the qualitative belief propagation algorithm for evaluating the effect of knowing $\bar{E}$ (i.e., absence of signals of A.'s mobile devices), represented by the sign ($-$) on the far right-hand side, on the truthstate of other variables in the network.

These assignments allow us to formulate two conclusions. First, we can compute the sign of qualitative influence between the variable *E* and *H* based on the signs of the qualitative influences that are associated with each arc of the trail connecting these two variables. This amounts to collapsing the three arcs $H \rightarrow P$, $P \rightarrow M$ and $M \rightarrow E$ into a single arc $H \rightarrow E$. Its sign of qualitative influence is found by invoking the sign product operator[33] $\otimes$, that is $\delta_1 \otimes \delta_2 \otimes \delta_3$. In the case here, this gives $+ \otimes + \otimes + = +$. Second, we can compute the effect that observing $\bar{E}$ has on the variable *H*. We can consider this in terms of a qualitative belief propagation (Druzdzel and Henrion, 1993; Henrion et al., 1991) where the sign of each node of the network is initially set to 0 (Fig. 2 (i)). Next, the sign of the observation that is available for the evidence node *E* is entered into the network. In the case here, *no* signals of A.'s mobile devices were detected, which corresponds to the sign $-$. This sign, shown on the far right hand side of Fig. 2(ii), is used to update the sign of the node *E*, using the sign addition operator[34] $\oplus$. Next, the node *E* determines that its parent *M* needs updating: the sign-product ($\otimes$) of the sign of node *E* and the sign of the link is $+$, which is different from the current sign of the node *M* (i.e., 0). So node *E* sends a message to node *M* with a sign given by the sign-product of the sign of *E* and the sign of the arc connecting *E* and *M*, that is $- \otimes + = -$. Upon arrival of this message, node *M* updates its current sign as follows: $0 \oplus - = -$. Qualitative belief propagation continues in the described way up to the node representing the main propositions *H* (Fig. 2(ii)), where H_d is supported over H_p.

In spite of the fact that qualitative belief propagation in the network shown in Fig. 1 amounts to a rather basic application, it is useful here because it allows one to read from the labelled graph exactly how the evidence

30 Notice that in this conditioning of *M* on *P* we do not make a distinction between A.'s presence as the offender and for innocent reasons. If this distinction is to be made, an additional edge from node *H* to *M* needs to be adopted.

31 A lower probability for $\Pr(M|P, I)$ could be adopted if one wishes to consider that, as noted at the end of Section Application to the present case, A. would take precautions to prevent his mobile device to be detected, which can be achieved by not carrying it when being on the scene (P).

32 Further details on this result are given in the Appendix.

33 See Wellman (1990) for further details on this operator.

34 See above n. 33.

'propagates' through the network and how intermediate variables are affected during inference about the main proposition H.

Discussion and conclusions

In this paper, we have emphasized on the relevance and feasibility of using formal methods of logical reasoning under uncertainty, in particular graphical probability models (Biedermann and Taroni, 2006; Taroni et al., 2014), to help deal with digital evidence at trial, independently of the position taken by different participants in the legal process. These methods of analysis are already firmly established for a wide variety of forensic traces (e.g., Roberts and Aitken, 2013), but there still is much room to point out their usefulness with respect to digital evidence, in particular through case studies.

In the case study proposed in this paper, confronting the court's summing up of the evidence (Section The court's summing up) with the formal analysis pursued in Section Principles of scientific interpretation reveals a subtle breach. On the one hand, the output of the formal analysis agrees with the court's conclusion according to which the prosecution's case is not categorically refuted: but what is more, given assumptions that can enjoy a fairly wide intersubjective acceptance, the formal analysis shows that the evidence regarding the absence of signals of A.'s mobile devices ought to *decrease* the evaluator's belief in the prosecution's story. On the other hand, the formal analysis allows us to emphasize that this is only one side of the assessment. In fact, when decreasing one's belief in one proposition, then one must – by coherence – redistribute probability among the remaining alternative(s). In the case considered here, there is only one such alternative, which is that of the defense. In the same formal analysis, the evidence provides support for this alternative proposition over that of the prosecution. Hence, considering scientific evidence only from the prosecution's position hinders vital evidence for the defense to be brought to the decision maker's attention.

On a methodological account, it is relevant to emphasize that the above conclusions do *not* rely on probability assignments understood in a frequentist perspective of 'long runs', commonly associated with classical statistics. Hence, widespread objections invoking unfeasible repeatability and unavailability of base rates do not apply here. Instead, all conclusions derive from considering uncertainty about single events faced by individual evaluators, given their personal state of knowledge, in a way that generalizes basic principles of logic (Robertson and Vignaux, 1993).

As we have seen, the evaluation the Court did of the digital evidence in this case can be considered as incomplete. It is entirely legitimate at this stage of the proceedings since the standard of proof is closer to preponderance of evidence than proof beyond a reasonable doubt. However, it is vital that this one-sided evaluation of the evidence be absolutely limited to this early stage of the proceedings. Evaluating the evidence in this way at the stage of adjudication would buttress the rights of the defense and be detrimental to the search for the truth.

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Appendix

For the Bayesian network shown in Fig. 1, the likelihood ratio (LR) for the finding $\overline{E}$ with respect to the propositions H_p and H_d is

$$\mathrm{LR}_{\overline{E}|H} = \frac{\Pr(\overline{E}|H_p, I)}{\Pr(\overline{E}|H_d, I)}$$
$$= \frac{e_1[(1-m_1)(1-p_1)+(1-m_2)p_1]+e_2[m_1(1-p_1)+m_2p_1]}{e_1[(1-m_2)(1-p_2)+(1-m_2)p_2]+e_2[m_1(1-p_2)+m_2p_2]}$$

where

$$\Pr(\overline{P}|H_p, I) = p_1,\ \Pr(\overline{P}|H_d, I) = p_2,$$
$$\Pr(\overline{M}|P, I) = m_1,\ \Pr(\overline{M}|\overline{P}, I) = m_2,$$
$$\Pr(\overline{E}|M, I) = e_1,\ \text{and}\ \Pr(\overline{E}|\overline{M}, I) = e_2.$$

With probabilities assigned as in Table 2, the likelihood ratio in favour of H_d is about 10 ($\mathrm{LR}^{-1}_{\overline{E}|H} = 9.16$, value rounded to two decimals).

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