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Viewing sets of mutually unbiased bases as arcs in finite projective planes

Metod Saniga [a,*], Michel Planat [b]

[a] *Astronomical Institute, Slovak Academy of Sciences, 05960 Tatranská Lomnica, Slovak Republic*
[b] *Institut FEMTO-ST, CNRS, Laboratoire de Physique et Métrologie des Oscillateurs, 32 Avenue de l'Observatoire, F-25044 Besançon, France*

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Abstract

This note is a short conceptual elaboration of the conjecture of Saniga et al. [J. Opt. B: Quantum Semiclass 6 (2004) L19–L20] by regarding a set of mutually unbiased bases (MUBs) in a d-dimensional Hilbert space as an analogue of an arc in a (finite) projective plane of order d. Complete sets of MUBs thus correspond to $(d+1)$-arcs, i.e., ovals. In the Desarguesian case, the existence of two principally distinct kinds of ovals for $d = 2^n$ and $n \geqslant 3$, viz. conics and non-conics, implies the existence of two qualitatively different groups of the complete sets of MUBs for the Hilbert spaces of corresponding dimensions. A principally new class of complete sets of MUBs are those having their analogues in ovals in non-Desarguesian projective planes; the lowest dimension when this happens is $d = 9$.

It has for a long time been suspected but only recently fully recognized [1–4] that finite (projective and related) geometries may provide us with important clues for solving the problem of the maximum cardinality of MUBs for Hilbert spaces of finite dimensions d. It is well-known [5,6] that this number cannot be greater than $d + 1$ and that this limit is reached if d is a power of a prime. Yet, a still unanswered question is if there are non-prime-power values of d for which this bound is attained. On the other hand, the minimum number of MUBs was found to be three for all dimensions $d \geqslant 2$ [7]. Motivated by these facts, Saniga et al. [1] have conjectured that the question of the existence of the maximum, or complete, sets of MUBs in a d-dimensional Hilbert space if d differs from a prime power is intricately connected with the problem of whether there exist projective planes whose order d is not a power of a prime. This note aims at getting a deeper insight into this conjecture by introducing particular objects in a finite projective plane, the so-called ovals, which can be viewed as geometrical analogues of complete sets of MUBs.

We shall start with a more general geometrical object of a projective plane, viz. a k-arc—a set of k points, no three of which are collinear [see, e.g. 8,9]. From the definition it immediately follows that $k = 3$ is the minimum cardinality of such an object. If one requires, in addition, that there is at least one tangent (a line meeting it in a single point only) at each of its points, then the maximum cardinality of a k-arc is found to be $d + 1$, where d is the order of the projective plane [8,9]; these $(d + 1)$-arcs are called *ovals*. It is striking to observe that such k-arcs in a projective plane of order d

* Corresponding author. Tel.: +421 52 4467 866; fax: +421 52 4467 656.
E-mail address: msaniga@astro.sk (M. Saniga).

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and MUBs of a d-dimensional Hilbert space have the *same* cardinality bounds. Can, then, individual MUBs (of a d-dimensional Hilbert space) be simply viewed as points of some abstract projective plane (of order d) so that their basic combinatorial properties are qualitatively encoded in the geometry of k-arcs? A closer inspection of the algebraic geometrical properties of ovals suggests that this may indeed be the case.

To this end in view, we shall first show that every proper (non-composite) conic in $PG(2,d)$, a (Desarguesian) projective plane over the Galois field $GF(d)$, is an oval. A conic is the curve of second order

$$\mathcal{Q}: \quad \sum_{i\leqslant j} c_{ij} z_i z_j = 0, \quad i,j = 1,2,3, \tag{1}$$

where c_{ij} are regarded as fixed quantities and z_i as variables, the so-called homogeneous coordinates of the projective plane. The conic is degenerate (composite) if there exists a change of the coordinate system reducing Eq. (1) into a form of fewer variables; otherwise, the conic is proper (non-degenerate). It is well-known [see, e.g. 8] that the equation of any *proper* conic in $PG(2,d)$ can be brought into the canonical form

$$\widetilde{\mathcal{Q}}: \; z_1 z_2 - z_3^2 = 0. \tag{2}$$

From the last equation it follows that the points of $\widetilde{\mathcal{Q}}$ can be parametrized as $\varrho z_i = (\sigma^2,1,\sigma)$, $\varrho \neq 0$, and this implies that a proper conic in $PG(2,d)$ contains $d+1$ points; the point (1,0,0) and d other points specified by the sequences $(\sigma^2,1,\sigma)$ as the parameter σ runs through the d elements of $GF(d = p^n)$, p being a prime and n a positive integer. Moreover, it can easily be verified that any triple of distinct points of $\widetilde{\mathcal{Q}}$ are linearly independent (i.e. not on the same line), as [10]

$$\det \begin{pmatrix} 1 & 0 & 0 \\ \sigma_1^2 & 1 & \sigma_1 \\ \sigma_2^2 & 1 & \sigma_2 \end{pmatrix} = \sigma_2 - \sigma_1 \neq 0 \tag{3}$$

and

$$\det \begin{pmatrix} \sigma_1^2 & 1 & \sigma_1 \\ \sigma_2^2 & 1 & \sigma_2 \\ \sigma_3^2 & 1 & \sigma_3 \end{pmatrix} = (\sigma_1 - \sigma_2)(\sigma_2 - \sigma_3)(\sigma_3 - \sigma_1) \neq 0. \tag{4}$$

Hence, a proper conic of $PG(2,d)$ is indeed an oval. The converse statement is, however, true for d odd only; for d even and greater than four there also exist ovals which are *not* conics [8–11]. In order to see this explicitly, it suffices to recall that all the tangents to a proper conic $\mathcal{Q}$ of $PG(2,d = 2^n)$ are concurrent, i.e. pass via one and the same point, called the nucleus [8–11]. So, the conic $\mathcal{Q}$ together with its nucleus form a $(d+2)$-arc. Deleting from this $(d+2)$-arc a point belonging to $\mathcal{Q}$ leaves us with an oval which shares $d = 2^n$ points with $\mathcal{Q}$. Taking into account that a proper conic is uniquely specified by *five* of its points, it then follows that such an oval cannot be a conic if $n \geqslant 3$; for, indeed, if it were then it would have with $\mathcal{Q}$ more than five points in common and would thus coincide with it, a contradiction.

Let us rephrase these findings in terms of the above-introduced MUBs—k-arcs analogy. We see that whilst for any $d = p^n$ there exist complete sets (c-sets for short) of MUBs having their counterparts in proper conics, $d = 2^n$ with $n \geqslant 3$ also feature c-sets whose analogues are ovals which are not conics. In order words, our analogy implies that MUBs do not behave the same way in odd and even (power-of-prime) dimensions. And this is, indeed, the property that at the *number theoretical* level has been known since the seminal work of Wootters and Fields [5, see also 7], being there intimately linked with the fact that so-called Weil sums

$$\left| \sum_{k \in GF(p^n)} \exp\left(\frac{2\pi \mathrm{i}}{p} \mathrm{Tr}\,(mk^2 + nk) \right) \right|, \tag{5}$$

with $m,n \in GF(p^n)$ and the absolute trace operator "Tr" defined as

$$\mathrm{Tr}\,(\eta) \equiv \eta + \eta^p + \eta^{p^2} + \cdots + \eta^{p^{n-1}}, \quad \eta \in GF(p^n), \tag{6}$$

are non-zero (and equal to $\sqrt{p^n}$) for all $p > 2$, playing thus a key role for proving the mutual unbiasedness in these cases, but vanish for $p = 2$ [see e.g. 12]. In the light of our analogy, this difference acquires a qualitatively new, and more refined, algebraic-geometrical contents/footing. Remarkably, this refinement concerns especially even (2^n) dimensions, as we shall demonstrate next.

In the example above, we constructed a particular kind of an oval by adjoining to a proper conic its nucleus and then removing a point of the conic; such an oval, called a pointed-conic, was shown to be inequivalent to a conic for $n \geqslant 3$. However, for $n \geqslant 4$ there exists still another type of non-conic ovals, termed irregular ones, that cannot be constructed this way [see e.g. 8,11,13]. This intriguing hierarchy of oval's types is succinctly summarized in the following table:

n	1	2	3	$\geqslant 4$
Ordinary conic	Yes	Yes	Yes	Yes
Pointed-conic	No	No	Yes	Yes
Irregular oval	No	No	No	Yes

Pursuing our analogy to the extreme, one observes that whereas $d = 2$ and $d = 4$ can accommodate only one kind of c-sets of MUBs, viz. those present also in odd dimensions and having their counterparts in ordinary conics, $d = 8$ should already feature two different types and Hilbert spaces of $d \geqslant 16$ should be endowed with as many as three qualitatively different kinds of such sets. So, if this analogy holds, a new MUBs' physics is to be expected to emerge at the three-qubit level and become fully manifested for four- and higher-order-qubit states/configurations.

Finally, we shall briefly address the non-Desarguesian case. We start with an observation that the definition of an oval is expressed in purely combinatorial terms and so it equally well applies to finite *non*-Desarguesian planes. These planes, however, do not admit coordinatization in terms of any Galois field [14–16]; hence, the c-sets of MUBs corresponding to ovals in such planes must fundamentally differ from "Desarguesian" sets. The lowest order for which non-Desarguesian planes were found to exist is $d = 9$, and there are even three distinct kinds of them; this means that it is also two-qutrit states whose properties merit a careful inspection.[1] The most tantalizing aspect of this analogy is, however, the case where d is composite (i.e. not a prime power) because such projective planes, if they exist, must necessarily be non-Desarguesian [14,15]. So, if there exist c-sets of MUBs for d composite, their properties cannot be described in terms of *fields*; instead, one has to employ a more abstract concept, that of (planar) *ternary rings*, as these are proper systems for charting non-Desarguesian projective planes [15,16]. And this is perhaps the most serious implication of our approach and a serious challenge for further geometrically-oriented explorations of MUBs, especially given an important role that MUBs start playing in current quantum cryptographic schemes/protocols and quantum information theory in general.

As a concluding note, it is worth mentioning that the geometrical concepts and structures employed above also find their proper place in the theory of Cremonian space-times—a theory which aims at accounting for our perception of time and space [see, e.g. 19,20]. And as this theory was found to share a number of interesting features with another remarkable concept, that of Cantorian transfinite fractal space [see, e.g. 21,22], we would not be surprised if the physics of MUBs could eventually be formulated in a pure set-theoretic framework [23].

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[1] It is a really intriguing fact to realize here that the two smallest non-trivial dimensions our approach singles out, viz. $d = 8 = 2^3$ and $d = 9 = 3^2$, are precisely those (product dimensions) where the so-called *unextendible product bases* (UPBs) first appear [see, e.g. 17,18]. This indicates that our oval geometries may underlie a wider spectrum of finite-dimensional quantum structures than sole MUBs.

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